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Spatial-temporal estimation of evapotranspiration over Black Volta of West Africa

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Evapotranspiration is an important component necessary for ensuring efficient management of water resources for every river basin. The Bui Hydroelectric Plant completed early 2014 to provide electricity for the people of Ghana is located within the Black Volta River Basin of West Africa. With the construction of this plant and related developments, there is a need for attention to be paid to the conservation of water resources within this basin. This paper therefore assesses the spatial temporal behaviour of evapotranspiration within the basin from 2001 to 2013 and compares this with the average monthly rainfall estimates from 1983 to 2012. The assessment shows that the average monthly evapotranspiration is within 0 to 150 mm/month for the period assessed. However, significant variation exists between the years with a highly erratic pattern observed. The pattern of the rainfall indicates that the upstream portion of the basin receives lower rainfall compared to the downstream portion of the basin. This pattern is consistent with the overall variation of the evapotranspiration within the basin. This spatial-temporal behaviour is an important factor that needs to be considered by all stakeholders given the anticipated land-use changes expected within the basin coupled with likely future increases in temperatures resulting from climate change.

Key words: Evapotranspiration, moderate resolution imaging spectroradiometer 16 (MODIS16), satellite application facility (SAF), Tropical Applications of Meteorology using SATellite (TAMSAT) rainfall, Bui Hydroelectric plant.

INTRODUCTION

Evapotranspiration (ET) is one of the difficult hydrological cycle parameters to estimate. It is impossible to estimate directly both in-situ and through satellite data. As a result, there have been several studies over the past decade using various derived data/products to estimate evapotranspiration (Bastiaanssen, 2000; Minacapilli et al., 2009; Or and Hanks, 1992; Rana and Katerji, 2000; Rwasoka et al., 2011; Su et al., 2003, 2005; Sucksdorff and Ottle, 1990). The large number of studies highlights the significance of this parameter and its relevance to water resource managers and agriculturalist as it informs decisions on water budgets. The ET dynamics cannot be
directly quantified from satellite observations; as a result it is derived based on the assumption that surface variables have a direct influence on evapotranspiration (Choudhury, 1991). In the recent past, satellite data has provided a leap forward in the ability to indirectly estimate evapotranspiration fluxes in space and time, further boosting our ability to monitor the ET over large areas (Allen et al., 2007; Bastiaanssen, 2000; Su, 2002). The surface energy balance algorithm for land (SEBAL) is a remote sensing based model that can be used to estimate large-scale ET over an area (Bastiaanssen, 2000; Bastiaanssen et al., 1998a, b). The SEBAL model uses satellite derived data for the land surface characteristics such as the surface albedo, land surface temperature and vegetation index. This is then coupled with meteorological data (that is, wind speed, humidity, solar radiation and air temperature) to resolve and estimate the instantaneous energy balance and then extrapolated to obtain the daily evapotranspiration. Another remote sensing based model is the surface energy balance system (SEBS) which also uses a similar approach to SEBAL by combining satellite derived products and meteorological data to estimate evapotranspiration (Su, 2002, 2009). Several improved versions by different researchers have been proposed however these are all fundamentally derived from the basic concepts indicated by SEBAL and SEBS. Other methods which have also been used include Vegetation Index/Temperature Trapezoid (VITT) (Moran et al., 1994) and Mapping Evapotranspiration at high resolution with internalized calibration (METRIC) (Allen et al., 2007).

Building on these fundamentals of remotely sensed ET products, the National Aeronautics and Space Administration (NASA) developed the moderate resolution imaging spectroradiometer (MODIS). The remotely sensed MODIS has both vegetative and land surface products. Mu et al. (2007) developed global evapotranspiration algorithm based on the remotely sensed MODIS data and global meteorological data. This algorithm was further improved by Mu et al. (2011) to improve the calculation of vegetation cover fraction, soil heat flux estimation and resistances for stomatal, aerodynamic and boundary layer. On the other hand, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) has also developed products under the land surface analysis satellite applications facility (LSA SAF) initiatives. LSA-SAF ET algorithm is one of the first kind to derive quasi-real time ET over large areas such as Europe, Africa and South America using remote sensing. It uses the meteosat second generation (MSG) to derive ET at high temporal scale over large areas.

For the Black Volta Basin of West Africa that is data scarce, the availability of these remotely sensed data provide a critical gap filling for understanding water budgets in the basin. Generally, in-situ stations within the basin are limited, and hence for real time decision making; it is imperative to support this with remotely sensed data.

In the Volta Basin, a number of researches have been conducted on the estimation of evapotranspiration using remote sensing methods (Hafeez et al., 2007; Mu et al., 2011b; Opoku-Duah et al., 2008) and others with water balance approach (Friesen et al., 2005; Kunstmann and Jung, 2007; Oguntunde et al., 2006). The Volta Basin consists of the Black, White and Oti River Basins. Most work has been conducted in the White Basin and Oti River Basin, there is no clear studies on the application of remote sensing techniques for estimation of ET in the Black Volta Basin. With the increasing relevance of the Black Volta to the economies of Ghana and Cote D’Ivoire, the water budget analysis in terms of the losses – ET become crucial.

The availability of MODIS ET and LSA SAF ET provides adequate spatially and temporally information that practitioners can use to inform decision making as it relates to water budgets in river basins. The objective of the paper is to estimate the spatial temporal ET over the Black River Basin using remote sensing approaches with data from MODIS ET and LSA SAF ET from 2001 to 2014. The products adopted are to assess and gain an understanding of the spatial-temporal ET variability between the 2001 and 2014 for the Black Volta Basin of West Africa; providing useful information for this important basin of West Africa given its socio-economic contribution to Ghana and neighbouring countries.

MATERIALS AND METHODS

Study area

The Black Volta River which is a tributary of the White Volta River flows through Ghana for about 1352 km before it joins the White Volta Basin. The Black Volta River Basin covers an area of 147000 km² and forms part of the international border between the La Cote D’Ivoire and Ghana, and Burkina Faso and Ghana. The basin has a tropical climate with temperatures averaging 24°C and a double maxima rainfall pattern. Average annual rainfalls for the northern and southern parts of the basin are 1000 and 1400 mm, respectively.

With the completion of the 400 MW Hydroelectric Project at Bui Gorge at the south end of the Bui National Park in Ghana in 2014, the basin has become very important on the national and international agenda as there is now a heightened need to monitor closely the water budgets in this basin to ensure sustainable management of the water resources. This is because the Bui Hydro plant is the second largest hydroelectric plant in the country after the Akosombo Dam. Figure 1 shows the basin including the Bui reservoir.

Datasets

MODIS global ET

The MODIS is aboard the Terra and Aqua satellites. The Terra’s
Figure 1. Black Volta Basin showing Bui Reservoir.

orbit around the Earth is programmed to pass from north to south and across the equator in the morning while the Aqua from south to north over the equator in the afternoon. The Terra and Aqua views the complete Earth in every 1 to 2 days and hence provide adequate information to monitor environmental fluxes. The MODIS16 ET datasets are estimated using the improved ET algorithm from Mu et al. (2011) over the previous (Mu et al., 2007). The ET algorithm is based on the Penman-Monteith equation with the concept that surface resistance is an effective resistance to evaporation from land surface and transpiration plant canopy. The MOD16 monthly global ET dataset are 5600 m spatial resolution at the equator. Due to its coarse resolution of the product, it is appropriate for the study of large areas or continental scale but not suitable for smaller watersheds. It would also be interesting if the regular production of such products was implemented so that on a timely basis, MODIS ET products could be obtained based on the algorithm in real time. The dataset covers a time period of 2000 to 2012, and, it is expected that in the future the dataset will be produced and posted periodically but this is not in real-time. Data for the period 2000 to 2012 was downloaded from ftp://ftp.ntsg.umt.edu/pub/MODIS/NTSG_Products/MOD16/.

LSASAF Global ET

The EUMETSAT LSA SAF is part of the SAF Network, a set of specialized development and processing centres, serving as EUMETSAT distributed Applications Ground Segment (LSA SAF, 2011). The SAF network supplements the product-oriented activities at the EUMETSAT Central Facility in Darmstadt. The prime purpose of the LSA SAF is to take full advantage of remotely sensed data to measure land surface variables that are of relevance; for supporting applications in meteorology (http://landsaf.meteo.pt/). ET is therefore one of the products developed by the LSA SAF.

The ET algorithm developed by the LSA SAF uses the quantification of flux of water vapour from the ground surface (that is, soil and canopy) into the atmosphere using derived products from the Meteosat Second Generation (MSG) satellites. The method mimics the physical approach and can be simplified as a simplified soil-vegetation-atmosphere transfer (SVAT) module adapted to integrate forcing satellite remote sensing (SRS) derived data with data from numerical weather products (NWP). The physics of the model on the Tiled European Centre for Medium-Range
The ET products for both LSA SAF and MODIS16 were correlated to check their comparability. The spatial correlation between the two datasets was relatively good (that is, $R^2$ is 0.77). This suggested that the datasets could be used to evaluate and understand the spatial-temporal behaviour for the study area. The monthly MODIS ET products have been validated (Mu et al., 2011a); however these products are only available from 2000 to 2012. The LSA SAF daily ET products on the other hand were only available from July 2010. Therefore, the LSA SAF ET daily products were first resampled to the same spatial resolution as the MODIS16 ET and then, used to derive the monthly ET for the period 2013 to 2014. In Integrated Land and Water Information System (ILWIS) open, the resampling LSA SAF ET was done by choosing the georeference of the MODIS16 ET map. The integration of the two datasets provided a long-series dynamics of the Black Volta River Basin from 2000 to 2014.

To understand the spatial behaviour of the monthly ET within the basin, 25 points (Figure 2) were distributed throughout the basin with the various monthly ET quantities from each location compared for each year for the whole period. This provided evidence of the dynamic spatial and temporal behaviour within the basin.

RESULTS AND DISCUSSION

The results of the estimated monthly ET are provided in Figure 5 for the 12 year period (2001 to 2013). The estimation from 2001 to 2012 was obtained from the MODIS16 Global ET. For the year 2013, ET estimated from the LSA SAF. The 12 year period ET estimation shows an average monthly distribution of 2 to 150 mm/month from 2001 to 2013 with the exception of the year 2010, where the ET quantities were slightly higher. The upstream portion of the basin (as indicated in Figure 2) tends to show very low average monthly ET estimates (2 to 50 mm/month) whereas the downstream portion of the basin shows high of 50 to 200 mm/month. There is an apparent exception for the year 2013 where some locations in the upstream portion of the basin receive ET estimates as high as 150 mm/month. It also shows that the portion of the basin located in the Brong-Ahafo Region of Ghana has higher ET estimates for the whole period compared to the rest of the basin. The average monthly ET for this part within Ghana is within the range of 100 to 200 mm/month. The part located within the La Cote D’Ivoire also receives the second highest ET estimates for the period (50 to 100 mm/month).

The landcover of the basin describes a variation of terrestrial woodlands, herbs and cultivated areas (Figure 3). This is reflective of the major economic activity in the basin as agriculturally based. Therefore, variations between climatological rainfall estimates for the period 1983-2012. This data is currently available at: http://www.met.reading.ac.uk/~tamsat/public_data/TAMSAT_clim_monthly.zip. The TAMSAT rainfall estimates are produced for Africa using the Meteosat thermal infrared observations. The TAMSAT rainfall estimation algorithm is calibrated using historic rain gauge records providing monthly and regional calibration parameters in both real and historical time scales.
different landcover types in the area are expected to be changing over time. Now, there is however a clear distinction between the upstream and the downstream that the upstream is predominately covered with semi-natural terrestrial herbs while the downstream is covered with semi-natural terrestrial woodlands. Though, the density of cover in each of these classes was not determined, it can be deduced that the upstream had higher ET estimates compared to the downstream as a result of more vegetative activity in the downstream. More vegetative cover in the downstream results in higher transpiration, hence increasing the amount of ET over the area. The temperature distribution in Figure 4 shows an erratic pattern between 2001 and 2013 measuring as low as 29.5°C (2001) to 30.7°C (2013). Though, the temperature measurements over the period are not spatially distributed, it helps to explain the general variation of the ET among the various years as a result of the effect of the temperature.

Figure 4 shows a relatively stable rainfall pattern observed across the different parts of the basin. The upstream portion of the basin labelled (II) is seen to have a relatively low monthly rainfall (30-60 mm) during the last 30 years compared to the downstream portion of the basin (60 to 86 mm). This possibly accounts for the observed spatial variation in ET with ET for the basin showing a similar overall spatial pattern. As would be expected due to issues of the erratic nature of the weather and climatic conditions, there are some yearly variability.

To understand the climatological conditions and to explain the possible reason for the high ET in the southern part of the basin compared to the rest of the basin, Figure 4 was developed. Figure 6(a) shows the average rainfall obtained from TAMSAT from 1983 to 2012 at the selected locations within the basin. Figure 6(b) shows the average monthly ET for the period 2001 to 2013.

The Bui Hydroelectric dam is located at the downstream portion of the basin (Figure 1). With the average monthly ET being relatively high around this location, this means that there is the need for careful attention to be paid to the management of the water resources in the reservoir to ensure that there is a consistent and sufficient water head for the generating power at the plant. With climate change, temperatures are expected to rise (Hulme et al., 2001; Kurukulasuriya et al., 2006; Stern, 2007). It is therefore imperative to consider this rise with the existing spatial-temporal behaviour of the evapotranspiration within the basin.

Generally, the temporal trend of the ET between years is rather erratic and does not follow any consistent pattern. However, the temporal trend with the downstream and upstream parts of the basin indicates that the downstream regularly receives higher rainfall and evapotranspiration values within a given year but between years, can be a rise or a fall. The spatial trend is rather vivid, showing lower evapotranspiration in the extreme
**Figure 4.** Average daily temperature in Black Volta River Basin. Source: GEONETCast Centre (2014).

**Figure 5.** Spatial Average Monthly ET variation within the Black Volta Basin (2001 to 2013).
upstream and showing highest evapotranspiration in the extreme downstream, with the middle part, showing average values.

With the completion of the Bui Hydroelectric plant in 2014, it is expected that socio-economic activity within the basin is bound to rise which no doubt will result in land-use modifications that could impact the hydrology and geomorphology of the basin. For example the downstream part of the basin has seen recent developments due to the establishment of new government institutions such as Bui Community, the Catholic University College and the University of Energy and Natural Resources. These are expected to translate to the building of new buildings and related infrastructure to house the activities of these newly established institutions.

Coupling these socio-economic changes with other changes such as climate change means that the basin characteristics could be significantly impacted. Large numbers of studies have indicated the impact of land-use change on rising temperatures (Dullinger et al., 2004; Piao et al., 2007). With these changes taking place, the average monthly ET would be expected to rise higher than what is shown between the period 2001 to 2013. If that were to happen, then special measures would be needed to ensure the Bui reservoir is able to conserve the water behind the dam, to enable constant and regular supply of water to the turbines. Such measures would be necessary to ensure that purposes for which the Bui Hydroelectric plant was established are consistently met. It would also be necessary that relevant stakeholders in the basin begin to discuss and coordinate across the countries involved (Ghana, La Cote D’Ivoire, Burkina Faso and Mali) to ensure that the water resources are efficiently managed, taking close consideration of the potential large losses e.g. evapotranspiration.

Conclusion

The Black Volta is a trans-boundary basin covering four countries – Ghana, Cote D’Ivoire, Burkina Faso and Mali. With the recent construction of the Bui Hydroelectric plant and associated dam, this has increased the possible socio-economic activities within the basin, owing to the relocation of small scale farmers and the establishment of new institutions to maintain the hydroelectric plant. With such new developments, the conservation of water resources has become critical. It is important that the water resources are managed appropriately to ensure that adequate water is available for the running of the hydroelectric plant.

The paper assessed the evapotranspiration in the basin from 2001 to 2013 to determine the spatial-temporal behaviour during this time. The study revealed that the average monthly evapotranspiration is estimated to be 0-150 mm/month for the whole period with the exemption of the year 2010 where estimates were about 200 mm/month. The average monthly evapotranspiration were compared with the average monthly rainfall estimates over a 30-year period. This comparison showed that the higher evapotranspiration estimates coincide with the high rainfall pattern within the basin. The study provides baseline information for decision makers and stakeholders within the basin to consider an integrated approach to managing the losses (that is, evapotranspiration) to ensure equitable sharing of the water resources within the basin for hydropower and also small scale farming activities.

Conflict of Interest

The authors of this publication have no financial issues or related interest that have influenced the study and therefore, expresses no conflict of interest whatsoever.

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Review

Contamination of groundwater due to underground coal gasification

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Underground coal gasification (UCG) generates potential groundwater pollution because it changes local hydrogeological parameters. Groundwater pollution is caused by diffusion and penetration of contaminants generated by UCG processes towards surrounding strata and possible leaching of residue by natural groundwater flow after gasification. A large number of hazardous water-borne contaminants were identified during different UCG operations conducted so far, and in some locations long-term groundwater contaminations were observed. Organic pollutants were detected after UCG process are phenols, benzene with its derivatives, polycyclic aromatic hydrocarbons (PAHs), heterocycles etc. and inorganic pollutants includes ammonia, mercury, zinc, sulphates, cyanides, heavy metals etc. Adsorption function of coal and surrounding strata makes a significant contribution to decrease the contaminants over time and distance from the burn cavity. Possible pollution control measures regarding UCG include identifying unsuitable zone, sitting a hydraulic barrier and pumping contaminated water out for surface disposal. The paper enumerates major pollutants identified in different UCG sites and its mitigation measures during gasification processes, and groundwater remediation after gasification.

Key words: Underground coal gasification, groundwater contamination, water influx.

INTRODUCTION

Underground coal gasification (UCG) is a procedure for extracting the synthesis gas (syngas) from in-situ underground coal seams that could not be economically extracted by conventional mining methods. UCG process produces gas suitable for high-efficiency power generation, chemical feedstock, fuel etc. The first available environmental data on UCG came from later United States trials, mainly regarding the Hanna and Hoe Creek UCG trails (Cooke and Oliver, 1983), at this site groundwater contamination monitoring was conducted pre- and post-UCG process. The results showed that UCG at shallow depths can pose a significant risk to groundwater in adjacent strata. UCG process, involves air/oxygen and steam pumped into the underground coal seam through an injection well. The introduction of an oxidizing gas produces heat, which partially combusts the coal in-situ and creates the syngas product, primarily composed of hydrogen (H₂), carbon monoxide (CO),

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carbon dioxide (CO₂) and methane (CH₄) (Stephens et al., 1985). The syngas is extracted from the UCG burn cavity by a production well, which brings the gas product to the surface for industrial uses. A schematic diagram of UCG process is shown in Figure 1. UCG is partly environmentally friendly due to non-discharge of tailing, decrease of sulfur emission, and non-discharge of ash, mercury and tar. In UCG process, physico-chemical interaction changes natural stress in the surrounding rock mass, which influences contaminants formation in the UCG reactor as well as inducing potential subsidence, and pollution of groundwater, surface water and atmospheric quality. Subsidence creates a hazard for any surface infrastructure that presents above the UCG zone and may create detrimental changes in surface or groundwater hydrology above the cavity (Torres et al., 2014). UCG cavity is a source of both gaseous and liquid pollutants. The risk of groundwater pollution from UCG depends on whether the contaminants can migrate beyond the immediate reaction zone to more sensitive groundwater areas. Transport of aqueous phase contaminants depends on permeability of in-situ rocks, geological setting of gasification reactor and hydrogeology of the adjacent area.

For the commercialization of UCG technology environmental impact studies, especially of groundwater pollution prevention and control is necessary. The paper identifies possibility of underground water pollution due to UCG and analyzes the fate of contaminants (organic and inorganic) as well as formulates strategies for groundwater pollution control.

GROUNDWATER CONTAMINATION BY UNDERGROUND COAL GASIFICATION

Contamination of ground water is considered as a serious environmental threat. Degradation of ground water can result from any of the following three sources (Ahern and Frazier, 1982):

(i) Organic contaminants in tars produced during carbonization or gasification;
(ii) Inorganic salts or trace elements in the leachate from the ash; and
(iii) Changes in flow patterns or rates resulting from subsidence or interconnection of aquifers by fracturing.

Groundwater contamination around UCG reactor is caused by dispersion and penetration of pyrolysis products of coal with migration of groundwater and escaped gases. During the gasification process, air or oxygen is injected with high pressure equal to or greater than the surroundings hydrostatic pressure (Pᵥ). Some of the gas products are therefore lost to the surrounding permeable media and overlying strata, as result of cracks in the overburden, as shown in Figure 2. In UCG reactor temperature is very high and due to this, solvent power of water increases, and density and viscosity of water decreases. After gasification coal ash is left in cavity and due to low pressure of reactor groundwater begins to enter into the gasifier. It may contain some higher molecular weight organic substances that are produced during pyrolysis of coal seam. The more volatile the product, the farther it is transported out into the surrounding coal strata before condensing or dissolving in groundwater. As the cavity cools and fills with water, the residual ash is leached, leading to increase in pH and in the concentration of many inorganic species. During this period, thermally driven convection currents transport some of the non-volatile inorganic contaminants from the ash into the surrounding formation. After that the concentrations of many contaminants will continue to change as a result of adsorption on the coal and strata or reactions among different species.

Due to hydraulic gradients, migration of groundwater will occur through coal seams and burned out areas which lie below the water table. This may cause soluble components sorb on ash or char to be leached out and transported away from the gasification site. An increase in dissolved organic material could result from partial dissolution of coal tars formed during gasification (Phillips and Muela, 1977).

Subsidence of the overburden above the UCG burn cavity also can cause groundwater contamination problems. An example of this phenomenon was found at the Hoe Creek UCG test site in the United States where aquifers cross connection occurred during gasification operations. The problem was transmission of pollutants generated in the burn zone through fractures caused by subsiding overburden into overlying aquifers. However, this should be avoided during the phase of choosing the study site (Burton et al., 2004). Initially at the time of gasification when the temperature of the gasification cavity is high, most of the returning water is vaporized and may be vented to the surface via the processing wells.

WATER INFLUX DURING UNDERGROUND COAL GASIFICATION PROCESS

Groundwater plays an important role in gas formation process during UCG. The major sources of water in the cavity areas are as follows:

(i) Water already available in the coal;
(ii) Water influx by permeable coal beds: It is the major source of water influx into the cavity; and
(iii) Water influx by overburden: It is the second major source of water into the cavity. Water influx by overburden is mainly two types, firstly when UCG process starts, water influx happen due to permeability of
rock overburden as shown in Figure 3, and secondly as coal burns away during UCG and overburden is exposed to intense heating. This causes extensive spalling of rock as it dries. Rock is exposed to thermal stresses and steam pressure (Sury et al., 2004).

Role of water in UCG process depends on whether the water influx is into the hot UCG cavity or downstream into the carbonized link zone. Water influx into the cavity can participate in gasification reaction and downstream into the carbonized link can participate directly in water-gas shift reaction which exchanges carbon monoxide for hydrogen, and indirectly in the methanation reaction; furthermore, it cools the product gas and thus decreases the potential for surface heat exchange to recover the sensible heat of the product gas but, at the same time, reduces high temperature corrosion of the production well and surface piping system. The amount of water flowing in is measured and controlled by the ratio of water to gasified coal (W/W). When the water influx ratio is higher than 0.5, a normal gasification process ceases at temperatures below 800°C. Therefore, a controlled groundwater influx is very important for enhanced-hydrogen gas preparation in UCG field tests by using the stored heat energy underground (Shu-qin et al., 2008).

Important reactions of underground coal gasification

The controlled gasification of UCG process involves burning of coal with air or other oxidants with complex series of reactions including carbonization, distillation, oxidation, reduction, pyrolysis, water-gas shift conversion, water-gas reaction, methanation and Boudouard reactions (Haider, 2012). The followings are
Effect of aquifer interconnection

Aquifer interconnection due to UCG process is investigated in Hoe Creek II and Hoe Creek III experiment in Wyoming (Stone et al., 1982). Aquifer interconnection would be happened when two coal seams are gasified in a column and a strata lies between them. After gasification of both coal seams (gasification process started at first lower coal seam) and the strata may be collapsed, depending on the strata strain and aquifers interconnect to each other. So, due to aquifer interconnection possibilities of groundwater contamination increases.

GOVERNING EQUATION OF GROUNDWATER FLOW AND TRANSPORT

Ground water flow equation

The two-dimensional equation of continuity for flow in one aquifer to multi-aquifer systems is represented by the following equation (Contractor and Shreiber, 1987):

\[
\frac{\partial}{\partial x}(K_x B_i \frac{\partial}{\partial x}(h_i)) + \frac{\partial}{\partial y}(K_y B_i \frac{\partial}{\partial y}(h_i)) + \frac{r}{B_i} (h_{i+1} - h_1) \frac{K_{lb}}{B_{lb}} (h_{i+1} - h_i) = S_i \frac{\partial}{\partial x}(h_i) \tag{1}
\]

Where, \( K_x, K_y \) are the permeabilities in x, y directions, \( h_{i-1}, h_i, h_{i+1} \) are piezometric heads in Aquifers I-1, I, I+1; \( B_i \) is the saturated thickness of Aquifer I; \( r \) is the recharge into the aquifer; \( Q_i \) is the pumping rate from aquifer I; \( K_{la}, K_{lb} \) are the permeabilities of aquitards above and below aquifer I; \( B_{la}, B_{lb} \) are the saturated thicknesses of aquitards above and below aquifer I; and \( S_i \) is the storage coefficient of aquifer I. For derivation of equation some essential assumptions has taken into consideration, such as water is homogeneous with constant density, Darcy’s law is valid, the Dupuit approximation is assumed to be valid, one dimensional vertical flow is assumed to occur in the aquitards without storativity effects, the off-diagonal terms of the conductivity tensor \( K_{xy} \) is equal to zero; and \( x \) and \( y \) being the principal axes.

Water quality model

Two-dimensional equation for mass transport is described below:

\[
\frac{\partial}{\partial t} (RC) = \frac{\partial}{\partial x}(D_{xx} \frac{\partial C}{\partial x} + D_{xy} \frac{\partial C}{\partial y}) - V_x C + \frac{\partial}{\partial y}(D_{yx} \frac{\partial C}{\partial x} + D_{yy} \frac{\partial C}{\partial y}) V_y C + \mu C + \gamma \sum \eta C + F_{i+1} + F_{i-1} \tag{2}
\]

Where, \( C \) is concentration; \( R \) is the retardation factor; \( D_{xx}, D_{xy}, D_{yx}, D_{yy} \) are dispersion coefficients; \( V_x, V_y \) are seepage velocity components in x, y direction; \( \mu \) is decay coefficient; \( \gamma \) is the recharge parameter; \( \sum \eta C \) is the effect of pumping summed over the number of wells, \( \eta \) being the discharge constant; \( F_{i+1} \) is the interaction effect with the aquifer above I; \( F_{i-1} \) is the interaction effect with the aquifer below I.

Now, \( F_{i-1} \) is interaction of aquifer I with aquifer I-1 above it.

\[
F_{i-1} = \begin{cases} 
\frac{K_{la}}{n_i B_i} h_{i+1} - h_i C_{i-1}, & \text{if } h_{i+1} > h_i \\
\frac{K_{lb}}{n_i B_i} h_{i-1} - h_i C_{i-1}, & \text{if } h_{i+1} < h_i 
\end{cases}
\]

Where \( n_i \) is the effective porosity of aquifer I and \( F_{i+1} \) is interaction of aquifer I with aquifer I+1 below it.

\[
F_{i+1} = \begin{cases} 
\frac{K_{lb}}{n_i B_i} h_{i+1} - h_i C_{i+1}, & \text{if } h_{i+1} > h_i \\
\frac{K_{la}}{n_i B_i} h_{i+1} - h_i C_{i+1}, & \text{if } h_{i+1} < h_i 
\end{cases}
\]

The dispersion coefficients are related to the velocity of ground water flow and to the nature of the aquifer using significant reactions involved during UCG process:

(i) Oxidation reaction: \( C + O_2 \rightarrow CO_2 + 393.8 \text{ MJ/kmol} \)
(ii) Partial oxidation: \( 2C + O_2 \rightarrow 2CO_2 + 231.4 \text{ MJ/kmol} \)
(iii) Oxidation: \( 2CO + O_2 \rightarrow 2CO_2 + 571.1 \text{ MJ/kmol} \)
(iv) Reduction/ Boudouard reaction: \( C + CO \rightarrow 2CO + 131.5 \text{ MJ/kmol} \)
(v) Hydrogenous water gas reaction: \( C + H_2O \rightarrow CO + H_2 \rightarrow 131.5 \text{ MJ/kmol} \)
(vi) Shift conversion: \( CO + H_2O \rightarrow CO_2 + H_2 \rightarrow 42.3 \text{ MJ/kmol} \)
(vii) Methanation: \( CO + 3H_2 \rightarrow CH_4 + H_2O + 206.0 \text{ kJ/mol} \)
(viii) Hydrogenation gasification: \( C + 2H_2 \rightarrow CH_4 + 87.5 \text{ kJ/mol} \).
Scheidegger’s equation.

\[ D_{ij} = \alpha_{ij} \frac{V_m V_n}{V} \quad (3) \]

Where, \( \alpha_{ij} \) = the dispersivity of the aquifer (dimensions of length), \( V_m, V_n \) = components of velocity in m, n direction, respectively, \( V \) = the magnitude of the velocity.

\[ = \left( (V_m)^2 + (V_n)^2 \right)^{1/2} \]

An isotropic aquifer dispersivity tensor defined in terms of two constants. These are the longitudinal and transverse dispersivities of the aquifer (\( \alpha_L \) and \( \alpha_T \), respectively). These are related to longitudinal and transverse dispersion coefficients by:

\[ D_L = \alpha_L V \text{ and } D_T = \alpha_T V \]

After expanding Equation (3) and substituting Scheidegger’s identities, the components of the dispersion coefficient for two-dimensional flow in an isotropic aquifer are:

\[ D_{XX} = D_L \left( \frac{v_x}{v} \right)^2 + D_T \left( \frac{v_y}{v} \right)^2 \]

\[ D_{yy} = D_T \left( \frac{v_y}{v} \right)^2 + D_L \left( \frac{v_x}{v} \right)^2 \]

\[ D_{xy} = D_{yx} = (D_L - D_T) \frac{v_x v_y}{v^2} \]

These essential assumptions were made in the derivation of equation are that the solute moves in a saturated, medium is porous, the solute concentration does not affect the density and viscosity of the water in the aquifer, and the dispersion coefficients are assumed to be proportional to the velocity, hence can vary with time from node to node.

**TYPES OF GROUNDWATER CONTAMINANT**

**Organic contaminants**

In laboratory and field studies, it has been observed that sorption of contaminants on aquifer substrate is an important mechanism that acts to decrease the concentration of contaminants in groundwater over time. However, certain contaminants are not sorbed sufficiently to alleviate concern for their transport in groundwater aquifers. The results (laboratory and field studies) specify that after a time period organic contaminants concentration are decreased and composition are changed. Phenols and low molecular weight aromatic hydrocarbons persist in solution while less soluble components such as three, four, and five-ring aromatic hydrocarbons are removed by sorption (Stuermer et al., 1982). The major organic groundwater contamination identified as phenols. Phenol is a constituent whose maximum concentration has varied from site to site. Maximum concentration is reported from range of 20 to 450 mg/L in six sites. Other organic pollutants were benzene, naphthalene, toluene, xylene, Dissolved Organic Compound (DOC), Polycyclic Aromatic Hydrocarbons (PAHs) as summarized in Table 1. According to data reported from six sites benzene is another organic substance of particular concern for its concentrations occurring at many of the sites and its designation as a human carcinogen. But benzene contamination is generally confined to within 9 m of the gasification cavities in the affected aquifers. As expected, volatile organics in the process tar and water, alone, showed the presence of over 250 different organic components (Campbell et al., 1979). The organic materials present in the groundwater were analyzed by two different procedures. In one procedure the dissolved organic carbon was fractionated into two broad groupings of hydrophilic and hydrophobic species. Each of these was then further fractionated into groups of acidic, basic and neutral compounds. In second procedure gas chromatography- mass spectroscopy (GC-MS) analysis was used to identify and quantify the concentrations of many of the individual organic compounds present (Campbell et al., 1979).

So, based on general solubility characteristics of these potential water pollutants, phenols pose the greatest threat, while pyridines and anilines are also regarded as soluble and therefore likely to be present in the water. Quinolones, which are somewhat less soluble, may be present at trace levels. Aromatic hydrocarbons are not expected to present a significant hazard to water quality (Phillips and Muela, 1977).

The post-gasification distribution of phenolic materials is a function of distance from burn cavity and time. Inside the burn cavity zone, phenolic concentration is found low due to strong adsorption and hence retardation in movement of aqueous phenol through a sub-bituminous coal bed (Wang, 1979). Organic pollutants found in UCG process are volatile and non-volatile. Volatile aromatic materials are benzene, toluene, xylenes and naphthalene. The more volatile (lower-molecular weight) are transported farther from the burn boundary. The groundwater from several wells of Hoe Creek I sampled after gasification was analyzed using GC-MS.

**Inorganic contaminants**

Coal is primarily consists of organic materials such as carbon, hydrogen, oxygen, nitrogen and sulfur. Inorganic material present is due to layers of clay, carbonate or mineral matter such as pyrite which are washed into the swamps along with plant material during initial stages of coalification. After combustion of coal, inorganic material is found mainly to be associated with ash, which can
Table 1. Baseline and maximum reported organic contaminates concentrations in six sites (Ahern and Frazier, 1982).

<table>
<thead>
<tr>
<th>Organic constituents</th>
<th>Hoe Creek I Base</th>
<th>Hoe Creek II Base</th>
<th>Hanna I Base</th>
<th>Hanna II Base</th>
<th>Fairfield Base</th>
<th>Tenn. Colony Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenols (mg/L)</td>
<td>0.001</td>
<td>-</td>
<td>45</td>
<td>45</td>
<td>-</td>
<td>270</td>
</tr>
<tr>
<td>Benzene (µg/L)</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>607</td>
</tr>
<tr>
<td>Naphthalene (µg/L)</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>640</td>
</tr>
<tr>
<td>Toluene (µg/L)</td>
<td>11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2200</td>
</tr>
<tr>
<td>Xylene (µg/L)</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1000</td>
</tr>
<tr>
<td>DOC (mg/L)</td>
<td>4</td>
<td>230</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.5</td>
</tr>
</tbody>
</table>

comprise from 3 to 20% of the original coal volume (Lang, 1982). Ash in the burn cavity was identified as a source of most of the inorganic constituents which moved with groundwater after gasification. Calcium, sulfate and hydroxide were the major inorganics leached out of ash. Hydroxide concentrations were lower in leachate from lignite ash than from bituminous and subbituminous ash (Humenick and Lang, 1980). Volatile inorganic species exhibit increasing concentration during UCG due to movement of volatile species out of the burn cavity. Ammonia produces during pyrolysis are detected at high concentrations in surrounding strata.

Several studies have identified changes in inorganic substances in groundwater due to the gasification process. Table 2 provides data for Tennessee Colony site in Texas which are representative of increase in inorganic groundwater constituents at other UCG sites. Soluble ash components are seen to increase total dissolved solid (TDS) concentrations in cavity water (Table 3). The materials include a wide array of ionic species, mainly calcium, sodium, sulphate and bicarbonate. There are, however, many other inorganic substances leached into the groundwater which are of interest, even though they are present in smaller amounts. These include calcium, aluminum, mercury, magnesium, sulphate, manganese, ammonia, arsenic, boron, iron, zinc, selenium, hydroxide and some radioactive materials such as uranium (Ahern and Frazier, 1982).

Field data and laboratory ash leaching experiments indicate that inorganic contaminates tend to increase due to ash leaching. Different results at different sites are probably due to coal and ash composition, gasifier temperatures, sampling techniques and natural water quality. Only one parameter, pH showed very large variations among investigators. Ash from Texas lignite showed little change in pH. Again, these differences could be accounted for by the inherent differences between coal and lignite, or may be site specific. Other groundwater contaminant grows during UCG process are total dissolved solids (TDS) and pH in different UCG sites (Table 3).

Surface water contaminations

Syngas produced by UCG contains a component of liquid or vaporized water which is removed from gas before the gas is used for power generation and chemical feedstock. This water contains residual hydrocarbons, benzenes, phenols and polycyclic aromatic hydrocarbons (PAHs) which are fully treatable. Potential pollution of surface water in UCG is extremely low, and the common pollutants are phenols, ammonia, chemical oxygen demand (COD), pH, conductivity and sulphides (Sury et al., 2004). The surface water can be affected by groundwater pumping and drilling operations, but the water pumped out to the surface may contain phenol (Green, 1999).

MIGRATION OF GROUNDWATER CONTAMINANTS

Migration with natural groundwater flow

Groundwater pollution due to UCG is a geo-environmental problem. Initial UCG process requires water for gasification of coal. Once the UCG process started cavity gradually increase. During burning process, cavity pressure is controlled for water influx and gas losses. Upon completion of burning, water present in aquifer begins to seep back into the burn cavity which
Table 2. Baseline and maximum reported inorganic contaminates concentrations in six sites (Ahern and Frazier, 1982).

<table>
<thead>
<tr>
<th>Type of constituents</th>
<th>Hoe Creek I Base</th>
<th>Hoe Creek II Base</th>
<th>Hanna I Base</th>
<th>Hanna II Base</th>
<th>Fairfield Base</th>
<th>Tenn. Colony Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cations (mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonium</td>
<td>0.6</td>
<td>72</td>
<td>-</td>
<td>-</td>
<td>1.0</td>
<td>100</td>
</tr>
<tr>
<td>Boron</td>
<td>0.09</td>
<td>0.5</td>
<td>0.8</td>
<td>0.6</td>
<td>0.06</td>
<td>0.3</td>
</tr>
<tr>
<td>Calcium</td>
<td>36</td>
<td>220</td>
<td>-</td>
<td>15</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>Iron</td>
<td>0.01</td>
<td>37</td>
<td>0.04</td>
<td>8</td>
<td>0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>Lead</td>
<td>0.001</td>
<td>0.041</td>
<td>0.03</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnesium</td>
<td>10</td>
<td>60</td>
<td>9</td>
<td>15</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Manganese</td>
<td>-</td>
<td>-</td>
<td>0.06</td>
<td>0.06</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zinc</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mercury</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Sulfate</td>
<td>150</td>
<td>1230</td>
<td>400</td>
<td>1600</td>
<td>4</td>
<td>1150</td>
</tr>
<tr>
<td>Cyanide</td>
<td>0.01</td>
<td>290</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sulfate</td>
<td>150</td>
<td>1230</td>
<td>400</td>
<td>1600</td>
<td>4</td>
<td>1150</td>
</tr>
<tr>
<td>Thiocyanate</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Anions (mg/L)

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Hoe Creek I Base</th>
<th>Hoe Creek II Base</th>
<th>Hanna I Base</th>
<th>Hanna II Base</th>
<th>Fairfield Base</th>
<th>Tenn. Colony Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDS (mg/L)</td>
<td>700</td>
<td>3400</td>
<td>1700</td>
<td>3300</td>
<td>350</td>
<td>2300</td>
</tr>
<tr>
<td>pH</td>
<td>7.5</td>
<td>6.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

ND-Not Determined.

Table 3. Baseline and maximum reported inorganic contaminates concentrations in six sites (Ahern and Frazier, 1982).

contains ash and rubble. Permeability in the cavity is assumed to be several orders of magnitude greater than that in the coal seam and porosity in the cavity is assumed to approach unity (Contractor and Schreiber, 1987). During water filling stage, products of combustion contaminate ground water. After a certain time, the cavity fills up and becomes part of the confined aquifer system. Storage coefficient of the cavity is now larger than that of the coal seam. A time is reached when flow occurs out of the cavity, taking with it the contaminants to be dispersed and sorbed in the aquifer. As started before and after gasification water in the coal seam (adjacent to the cavity) flows into it, picking up pollutants from the ash and char zone, and migrates from the cavity to adjacent aquifers (Sury et al., 2004).

Groundwater restoration

After completion of UCG process many organic and inorganic contaminants left in cavity, generated after UCG process. Phenol concentration in
groundwater is found in large amount because its solubility in water is high. Groundwater is function of time and distance from the reactor (Campbell et al., 1979). So, concentrations of contaminated groundwater restore as fresh water after a long time. Inorganic contaminates, including cations such as \( \text{Na}^+ \), \( \text{K}^+ \), \( \text{Mg}^{2+} \), \( \text{NH}_4^+ \) etc. and anions such as \( \text{SO}_4^{2-} \), \( \text{HCO}_3^- \), \( \text{Cl}^- \) etc. also showed a large decrease in concentration over time (Nordin, 1992).

MITIGATION OF GROUNDWATER CONTAMINATION

Site selection

Appropriate site selection is the best approach for groundwater pollution control. Before starting UCG process ensure the site is well characterized and the coal seam has limited connectivity with water sources. Therefore, selecting sites with favorable hydrogeology minimizes movement of contaminants. Selection of regions where overburden is expected to deform plastically reduces the concern of shearing of strata. Shearing can result in vertical propagation fractures that allows fluid communication between the gasification zone and surrounding groundwater (Moorhouse et al., 2010).

Appropriate sealing of wells and boreholes

Before starting UCG operation ensures that wells and boreholes used in the process are adequately sealed and maintain a ‘cone of depression’ in the groundwater around the reactor (Sury et al., 2004). Researchers have proposed several control technologies for containment, such as a hydraulic bypass around the contaminated zone, placing adsorbent clays within the cavity, placing a grout curtain around the contaminated zone and permeable reactor barrier. The permeable reactor barrier is filled with granulated activated carbon and peat for removal of hydrocarbons (Lutynski and Suponik, 2013). These contaminants are removed by physicochemical, chemical and biological processes.

Controlling the reactor pressure

Migration of hazards elements from UCG cavity could be reduced by maintaining reactor pressure (\( P \)) below the hydrostatic pressure (\( P_h \)). Installation of operational monitoring systems is used to detect gas losses and ensure that reactor pressure is maintained below hydrostatic. In this case, water flow from the surrounding aquifer in to the UCG cavity, presents transport of contaminants into adjacent aquifers. It is also found that gas escape, which is driving force for contaminant dispersal, could be substantially reduced. Therefore, during UCG operation continuously measures the reactor pressure for mitigation measures (Friedmann et al., 2006).

Pumping of contaminated water

Another concept for control would be pumping the contaminated water from the cavity and surrounding area, and treating or disposing of the water on the surface. This alternative would be effective for removal of highly mobile contaminants. These contaminants would consist of materials generated by ash leaching, such as soluble organic matter and ammonia (Cook and Oliver, 1983). Remaining material would be more insoluble and less mobile condensed organic matter around the periphery of the burn zone.

Abandonment practices

At the time of shutdown of UCG process gasification zone cool slowly and gas is continue to extract until the gasification process stops completely. In this way contaminants can be evacuated out of the gasification zone before the site is abandoned. Monitoring of groundwater contaminates for a period of time after the site is abandoned. The actual duration of monitoring will depend on the specific site (Moorhouse et al., 2010).

CONCLUSIONS

Groundwater pollution caused by UCG due to migration of water and gas dispersion to the surrounding permeable strata. The major pollutants identified in groundwater include organic and inorganic substances, TDS etc. Concentration of these pollutants decrease by increase of distance from the cavity, and after some time these decrease due to restoration of pollutant water. Migration of contaminated groundwater and restoration as well as some mitigation measures are specified for pollution free UCG operation. Major organic and inorganic substances, TDS and pH data indicate that baseline and maximum contaminated groundwater constituents vary depending on types of coal and operating parameters of UCG.

Conflict of Interest

The authors have not declared any conflict of interest.

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