CONSIDERATIONS FOR EVALUATING COALBED METHANE INFILTRATION POND SITES BASED ON SITE STUDIES IN THE POWDER RIVER BASIN OF MONTANA AND WYOMING[1]

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Abstract. Significant volumes of ground water are produced in association with coalbed-methane (CBM) production in the Powder River Basin in Montana and Wyoming. This water must be managed in a manner that is both economical and sensitive to the semi-arid agricultural area of southeastern Montana and northeastern Wyoming. Infiltration ponds are one of the primary methods of handling production water and have been in use in Montana and Wyoming for several years. A solid conceptual framework of the parameters that control water quality and flow allows for the selection of infiltration pond sites which maximize impoundment life and minimize impacts.

The ponds have several advantages in that they require a low initial investment and can help recharge the shallow ground-water system, which makes the production water available for future uses. However, as the infiltrated water moves through the shallow weathered bedrock, a series of chemical reactions typically take place (primarily dissolution and oxidation) which temporarily increase the total dissolved solids (TDS) due primarily to increases in Mg, Na, and SO_4. As the available salts are removed along the ground-water flow path through the bedrock, the concentrations of dissolved constituents in the ground water tend to decrease. Preliminary interpretations of data suggest that saturated paste extract (SPE) analyses and lithologic investigations may be used to predict the types of changes in water quality that can occur.

The fate and transport of the dissolved salts is controlled to a great extent by the rate of infiltration and the duration of saturated flow from the ponds. The rate of infiltration can be severely reduced as the clays in the pond floor and underlying material are exposed to the high SAR produced water, which causes dispersion and reduced vertical hydraulic conductivity. Order-of-magnitude decreases in vertical hydraulic conductivity have been observed, which represent a trade-off. First, the changes will effectively decrease the volume of water that can be managed via an individual pond. Secondly, the mobilized salts may be effectively sequestered by reduced ground-water flow; substantially reducing the temporal and geographic extent of impacts.

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Introduction

Significant volumes of ground water are produced in association with coalbed-methane (CBM) production in the Powder River Basin in Montana and Wyoming. This water must be managed in a manner that is both economical and sensitive to the semi-arid agricultural area of southeastern Montana and northeastern Wyoming. Infiltration ponds are one of the primary methods of handling production water and have been in use in Montana and Wyoming for several years. A solid conceptual framework of the parameters that control water quality and flow allows for the selection of infiltration pond sites which maximize impoundment life and minimize impacts.

Coalbed methane production

Water-management planning is a critical component of CBM development. Within the Powder River Basin in southeastern Montana, an area of approximately 5,500 square miles (Fig. 1), 7,500 to 26,000 CBM wells may be put into production during the next 20 years (BLM, 2003). The production of CBM requires that the hydrostatic pressure in the coal aquifers be reduced, which allows the methane to desorb from the coal surfaces. This requires the pumping of significant volumes of coalbed water from these aquifers, and the management of this water at the surface.

The productive life of individual wells is not yet known for the Powder River Basin, but estimates range from 5 years to 20 years (BLM, 2003). Water production rates from individual wells decreases with time. This decreasing production rate, represented by the decline curve for producing wells in Montana in Fig. 2, indicates discharge rates for individual wells between 5 and 10 gallons per minute (gpm) (27 to 55 cubic meters per day [m^3/day]) during the first year, decreasing to less than 3 gpm (16.4 m^3/day) after 6 years (Wheaton and others, 2006).

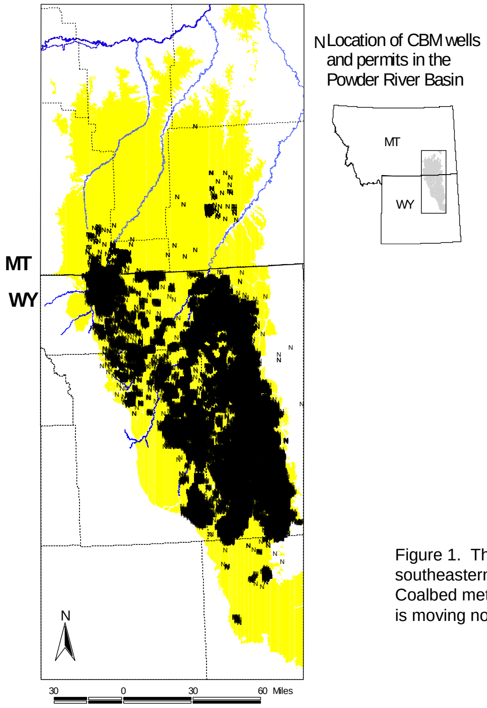

Figure 1. The Powder River Basin is located in southeastern Montana and northeastern Wyoming. Coalbed methane development started in Wyoming and is moving north in to Montana.

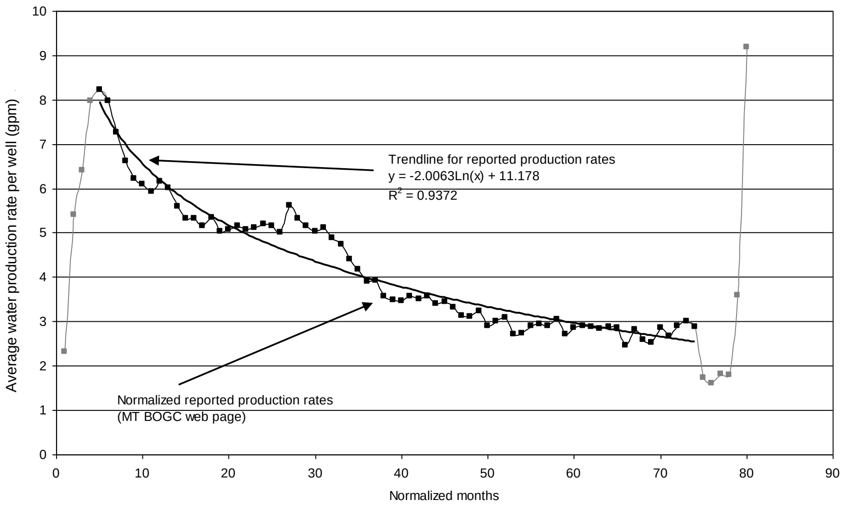

Figure 2 . Water-production rates from individual CBM wells decrease with time as the water-level in the coal aquifer decreases. Modified from Wheaton and others, 2006. Light grey data points on the curve were not included in the trend line as they are felt to represent water-management rather than hydrogeologic conditions

Water produced with CBM is chemically distinctive. It is high in bicarbonate relative to sulfate (reduced conditions); it has low concentrations of calcium and magnesium, and relatively high sodium concentrations (Van Voast, 2003). In Montana an average sodium adsorption ratio (SAR) of 47 and an average specific conductance (SC) of 2,200 umhos/cm was used for the coalbed methane environmental analysis (BLM, 2003). By comparison, during water year 2005, the Tongue River at the Montana-Wyoming state line gauging station had mean monthly SAR values which ranged from 0.4 to 1.0, and mean monthly SC values which ranged from 250 to 773 umhos/cm (Bobst, 2006).

Due to its salinity and sodium concentrations, and the surface water standards that have been adopted by the Montana Board of Environmental Review (ARM 17.30.670), it is anticipated that only a small percentage of the total produced water volume will be able to be discharged to surface waters under Montana Pollutant Discharge Elimination System (MPDES) permits without prior treatment. Therefore, other methods of managing CBM waters are expected to be widely used, such as injection, managed irrigation, evaporation ponds, and infiltration ponds.

Infiltration basins are commonly used in Wyoming and Montana. They are an inexpensive means of disposing of produced water, and their ability to store water allows for more flexibility in water management. Also, the produced water, which comes from primary aquifers in the area, may recharge the shallow ground-water system, which makes the produced water available for future use; however the infiltrated water tends to move laterally as well as vertically and stays fairly shallow. The high-SAR produced water also causes dispersion of clays in the pond floor, and therefore the infiltration rates will decrease over time. As the infiltrated water moves through and saturates previously unsaturated shallow weathered bedrock, a series of chemical reactions take place (primarily dissolution and oxidation), which increases TDS, Mg, and SO_4 concentrations (Wheaton and Brown, 2005). Impacts from infiltration ponds are dependent on the materials which immediately underlie the pond, the depth to groundwater, distance to outcrop, and other site-specific hydrogeologic parameters. Depending on the setting, infiltrated water, along with its salt load and the salt that it picks up in the subsurface, may: 1) percolate downward to recharge existing aquifers (saturated flow to the underlying aquifer); 2) intersect an aquitard and flow to outcrop (saturated flow to outcrop); or 3) percolate downward while the pond is in use, but not achieve saturated flow to an underlying aquifer or to outcrop (water migrates as vapor, leaving the salt behind). In this third case, the salt load could be effectively sequestered as the recharge source is eliminated when the pond seals or is abandoned.

Coal-strip mines create a similar situation in reclaimed areas where the previously unsaturated spoils material (overburden) becomes part of the flow system for ground water. Predicting spoils-water quality is an integral part of permitting coal mines, and some of the methods used there are applicable to CBM infiltration basins. Particularly, saturated paste-extract (SPE) data may help define percentages of major cations in the resultant water samples.

Study sites

Flowing stock-well channels in southeastern Montana

At 10 sites in southeastern Montana, 15 borings were augered in channels flowing from stock wells. The quality of the water flowing from these stock wells at all of the sites fits the signature for CBM-produced water; it is high in Na, low in Ca and Mg, with little or no SO_4. These sites represent soil conditions and ground-water quality conditions in Powder River Basin in Montana after long-term infiltration of this water. The water from the flowing wells has been allowed to flow freely through discharge channels for over 10 years. Leakage through the channel bottoms was expected to create saturated conditions directly beneath the channels that would allow investigation of the long-term effects of high-SAR water on rates of infiltration and changes in water quality as it infiltrates and interacts with the underlying materials.

Far less infiltration occurred at these sites than was anticipated. Even though the borings were augered in the most favorable zone for concentration of infiltrated water, cuttings demonstrate that only 5 of the 15 borings penetrated damp or wet material. The water flowing in the channels was lost to evaporation and transpiration or left the study area as surface flow. Moist drill cuttings indicated that small amounts of water infiltrated to the subsurface, but not generally in sufficient quantities to create saturated conditions. Given the extremely low infiltration rates, direct measurement of infiltration rates and resulting water chemistry was not feasible.

Sodium adsorption ratios (SAR) in the water discharging from the flowing wells are very high, ranging from 34.8 to 72.5. The high SAR values appear to have caused dispersion of the clay particles in the flow channels and directly beneath the channels. Dispersed clay particles effectively plug the pores in the affected portion of the subsurface profile, blocking infiltration of water. Clay contents at the sites range from 11 percent to 51 percent. Analyses of the relationship between clay content and long-term infiltration did not reveal any direct relationship between percent clay, silt or sand and infiltration values. Two sites with clay content of 14% were underlain by dry material while infiltration was observed at sites with clay content as high as 26%.

It appears that given sufficient time (in these cases more than 10 years) clay dispersion in materials with even low clay content can result in plugged pore throats. Under some conditions infiltration can occur with moderate clay content, even after many years of exposure to high-SAR water. This may be a function of calcium and magnesium availability since the SAR can be lowered by the dissolution of natural calcium- and magnesium-bearing minerals.

Coal Creek Infiltration Pond

A detailed study has been underway at a CBM infiltration pond in the Coal Creek watershed, near Ucross, Wyoming, since 2002. Results of this work through 2004 are presented and discussed in Wheaton and Brown (2005). Results presented in that paper document changes in ground-water quality beneath the pond and the use of saturated paste extracts to predict those changes. The discussion of the Coal Creek pond site in this current paper is limited to changes in vertical hydraulic conductivity based on the water budget for the pond.

The pond was constructed in gently sloping uplands about ¼ mile (0.4 km) south of the Coal Creek channel. Prior to CBM-produced-water discharge to the pond, monitoring wells were installed through the pond floor and around the pond (Fig. 3). The bedrock formation in this area is the Wasatch Formation. The pond was excavated through colluvial material to the top of the weathered bedrock. The underlying material consists of interbedded clay, sandstone, siltstone and coal. The stratigraphy underlying the pond, based on gamma logs from the monitoring wells, is shown in Fig. 3.

A water budget was constructed for the pond, based on reported monthly total CBM-produced water discharge (Wyoming Board of Oil and Gas Conservation Commission web page, http://wogcc.state.wy.us/), precipitation data for the Clearmont, Wyoming meteorological station located 20 miles to the east, evaporation data during ice-free conditions (Payne, 2004), surveyed elevations and dimensions of the pond and the monitoring wells, and periodic pond stage and ground-water level measurements. Monthly data are listed in Table 1, along with the results of the water-budget calculations. Pond stage and ground-water levels for months when field visits were not made were interpolated from earlier and later months.

Vertical hydraulic conductivity, listed in Table 1, represents values averaged over the entire area of the pond floor. Early values, when the pond was first receiving CBM water, represents unsaturated conditions (unsaturated hydraulic conductivity), preferential flow paths, or some combination of both. Later values represent saturated flow and changes in the physical conditions of the subsurface material.

Water was discharged into the pond over a 16-month period from July, 2003 through October, 2004. By June, 2006 the pond was dry. Total inflow to the pond was 666,400 ft^3 (18,900 m^3) and of that 16 percent was precipitation and 84 percent was CBM-produced water. This entire volume of water was lost from the pond through one of two processes, evaporation and infiltration. Loss to evaporation is estimated to have been 203,200 ft^3 (5,750 m^3); therefore approximately 463,100 ft3 (13,100 m^3) of water (69 percent) infiltrated into the subsurface.

The details of the pond and the water budget parameters are shown in Fig. 4. The equation for the water budget is:

Inflow ± δStorage = Outflow

Inflow: CBM-produced water
Precipitation

δStorage: Change in the volume of the pond

Outflow: Evaporation
Infiltration

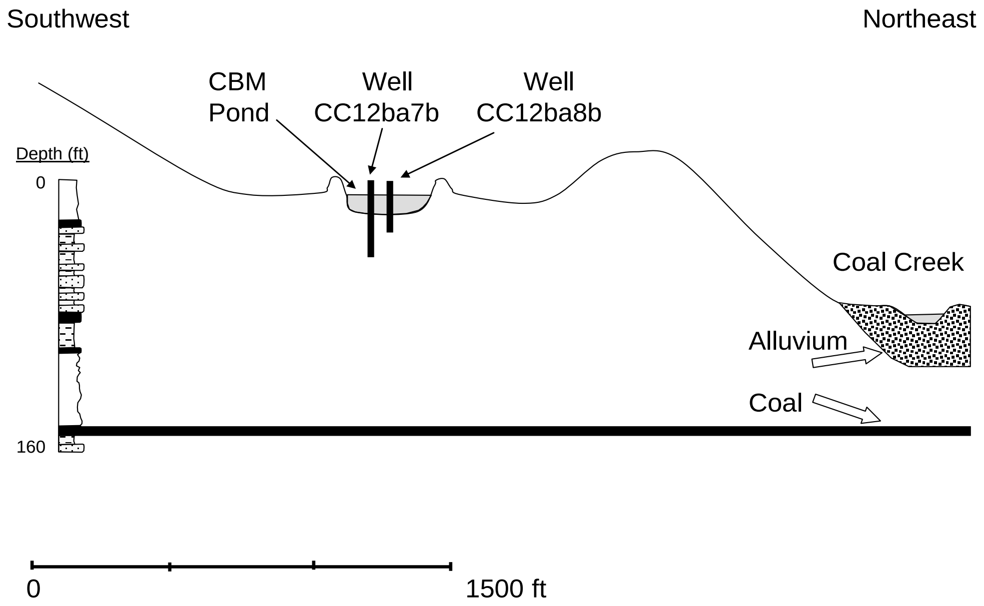

Figure 3 . Monitoring wells are completed in sandstone units beneath the off-channel infiltration pond at the Coal Creek site near Ucross, Wyoming.

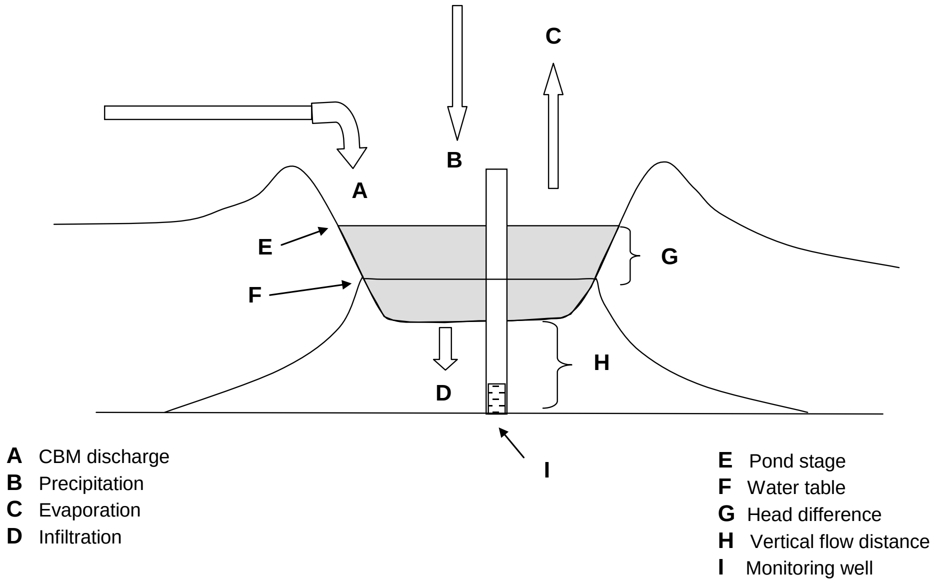

Figure 4 . Parameters used for the water budget for the Coal Creek site near Ucross, Wyoming.

Table 1. Water budget for the Coal Creek CBM infiltration pond near Ucross, Wyoming.

INFLOW (monthly totals)

Date	CBM-produced water discharge (ft3)	Precipitation (inches)	Precipitation (ft3)	Total inflow (ft3)
June-03	0	2.79	9817	9817
July-03	5171	0.31	1037	6208
August-03	3549	0.00	0	3549
September-03	0	1.11	3335	3335
October-03	0	0.12	340	340
November-03	19316	0.64	1781	21097
December-03	943	0.76	2139	3082
January-04	3745	0.59	1680	5425
February-04	0	0.75	2161	2161
March-04	0	0.21	612	612
April-04	82063	0.36	1061	83124
May-04	149246	1.94	6241	155487
June-04	64466	0.75	2403	66869
July-04	73657	2.84	9053	82710
August-04	55274	0.26	824	56098
September-04	50102	0.68	2146	52248
October-04	52197	0.75	2355	54552
November-04	0	0.03	94	94
December-04	0	0.18	559	559
January-05	0	0.35	1083	1083
February-05	0	0.26	797	797
March-05	0	1.36	4112	4112
April-05	0	2.95	8805	8805
May-05	0	4.19	12340	12340
June-05	0	1.34	3895	3895
July-05	0	1.20	3445	3445
August-05	0	0.63	1775	1775
September-05	0	0.70	1942	1942
October-05	0	2.49	7010	7010
November-05	0	0.25	717	717
December-05	0	0.38	1108	1108
January-06	0	0.00	0	0
February-06	0	0.07	214	214
March-06	0	0.44	1397	1397
April-06	0	0.73	2400	2400
May-06	0	1.34	4555	4555
June-06	0	0.98	3448	3448
TOTALS	559729	34.73	106679	666408

Precipitation values are from the National Weather Service database for Clearmont, WY. Evaporation rates are from Payne, 2004, during ice-free conditions.

Table 1. Continued

STORAGE (monthly totals)

Date	Pond Stage (ft above flloor)	Pond area (ft2)	Pond volume (ft3)	Change in storage (ft3)
June-03	0.00	0	0	0
July-03	0.23	4117	2059	2059
August-03	0.46	8234	4117	2058
September-03	0.69	12351	6176	2059
October-03	0.92	16468	8234	2058
November-03	1.15	18132	9724	1490
December-03	1.66	18920	22202	12478
January-04	2.17	19709	34679	12477
February-04	2.68	20497	47157	12478
March-04	3.19	21286	59635	12478
April-04	3.71	22090	72357	12722
May-04	7.90	28567	174869	102512
June-04	7.68	28232	169565	-5304
July-04	7.44	27860	163671	-5894
August-04	7.19	27475	157580	-6091
September-04	6.94	27090	151490	-6090
October-04	6.70	26705	145399	-6091
November-04	6.45	26333	139505	-5894
December-04	6.21	25948	133414	-6091
January-05	5.96	25563	127324	-6090
February-05	5.51	24872	116396	-10928
March-05	4.89	23917	101277	-15119
April-05	4.29	22993	86647	-14630
May-05	3.68	22037	71528	-15119
June-05	3.08	21113	56898	-14630
July-05	2.52	20250	43242	-13656
August-05	1.70	18978	23117	-20125
September-05	1.02	17931	6543	-16574
October-05	0.94	16880	8440	1897
November-05	0.87	15627	7813	-627
December-05	0.81	14499	7250	-563
January-06	0.76	13604	6802	-448
February-06	0.61	10919	5460	-1342
March-06	0.46	8234	4117	-1343
April-06	0.31	5549	2775	-1342

May-06	0.16	2864	1432	-1343
June-06	0.00	0	0	-1432
Total				0

Table 1. Continued

OUTFLOW (monthly totals)

Date	Evaporation (ft)	Evaporation (ft3)	Ground-water infiltration (ft3)	Total outflow (ft3)
June-03	0.53	4162	5655	9817
July-03	0.65	2659	1490	4149
August-03	0.59	4892	-3401	1491
September-03	0.45	5558	-4282	1276
October-03	0.31	5105	-6823	-1718
November-03	0.15	2720	16887	19607
December-03	0.00	0	-9396	-9396
January-04	0.00	0	-7052	-7052
February-04	0.12	2391	-12709	-10318
March-04	0.16	3299	-15165	-11866
April-04	0.30	6627	63775	70402
May-04	0.44	12546	40429	52975
June-04	0.53	14822	57351	72173
July-04	0.65	17993	70612	88605
August-04	0.59	16325	45865	62190
September-04	0.45	12191	46147	58338
October-04	0.31	8279	52364	60643
November-04	0.15	3950	2038	5988
December-04	0.00	0	6650	6650
January-05	0.00	0	7173	7173
February-05	0.12	2902	8823	11725
March-05	0.16	3707	15524	19231
April-05	0.30	6898	16537	23435
May-05	0.44	9678	17781	27459
June-05	0.53	11084	7441	18525
July-05	0.65	13078	4023	17101
August-05	0.59	11276	10624	21900
September-05	0.45	8069	10447	18516
October-05	0.31	5233	-120	5113
November-05	0.15	2344	-1000	1344
December-05	0.00	0	1671	1671
January-06	0.00	0	448	448
February-06	0.12	1274	282	1556
March-06	0.16	1276	1464	2740

April-06	0.30	1665	2077	3742
May-06	0.44	1258	4640	5898
June-06	0.39	0	4880	4880
				0
Total	11.44	203260	463150	666410

Table 1. Continued

VERTICAL HYDRAULIC CONDUCTIVITY

Date	Ground-water levels at 12BA8B (ft below pond floor)	Vertical gradient (ft/ft)	K (ft/d)
June-03	-5.18	0.89	0.0
July-03	-5.54	0.99	0.0
August-03	-5.89	1.09	-0.01
September-03	-6.25	1.19	-0.01
October-03	-6.25	1.23	-0.01
November-03	-6.25	1.26	0.02
December-03	-4.58	1.07	-0.02
January-04	-3.15	0.91	-0.01
February-04	-1.73	0.75	-0.03
March-04	-0.30	0.60	-0.04
April-04	1.12	0.44	0.2
May-04	5.51	0.41	0.1
June-04	5.13	0.44	0.2
July-04	4.75	0.46	0.2
August-04	4.38	0.48	0.1
September-04	4.00	0.50	0.1
October-04	3.62	0.53	0.1
November-04	3.24	0.55	0.00
December-04	2.87	0.57	0.01
January-05	2.49	0.59	0.02
February-05	1.98	0.60	0.02
March-05	1.24	0.62	0.0
April-05	0.50	0.65	0.0
May-05	-0.23	0.67	0.0
June-05	-0.97	0.69	0.0
July-05	-1.71	0.72	0.01
August-05	-3.10	0.82	0.02
September-05	-4.48	0.94	0.02
October-05	-5.05	1.02	0.0
November-05	-5.61	1.11	0.0
December-05	-6.18	1.19	0.0
January-06	-5.26	1.03	0.0
February-06	-5.25	1.00	0.0
March-06	-5.24	0.98	0.01
April-06	-5.24	0.95	0.0
May-06	-5.23	0.92	0.1
June-06	-5.22	0.89	0.0

The pond is surrounded by a berm that precludes surface water runoff entering the pond. There is no spillway and water levels did not reach the top of the berm, so there were no surface outflows. Monthly precipitation volumes were based on the area within the berm. Precipitation falling over the surface area of the pond during the month was added to the pond volume, and a volume equal to 50% of the precipitation falling over the area between the water surface and the top of the berm was also added to the pond volume as runoff. The storage capacity of the pond was calculated on 1-foot (0.3 m) intervals based on the pond dimensions and the bank slope. Monthly volumetric evaporation totals were based on average free-surface water evaporation rates multiplied by the pond surface area during that month. Using these parameters an estimate of infiltration volume was calculated.

Vertical hydraulic conductivity directly beneath the pond floor was calculated using the results of the water budget and water level data (Figure 4). The water-budget calculations provided the quantity of water that infiltrated through the pond floor on a monthly basis. A piezometer drilled through the pond floor and completed with a short screened interval at a total depth of 5.8 feet was monitored for ground-water levels. The vertical hydraulic conductivity was calculated using Darcy's Law:

$Q=-KIA$

$K_z = Q / (AI_z)$

Where

K_z Vertical hydraulic conductivity

Q Volume of water infiltrating through the pond floor

A Area of pond floor

I_z Vertical gradient (pond stage altitude – ground water altitude) / (pond floor altitude – base of aquifer)

Figure 5 shows monthly values for pond water levels, calculated evaporation and estimated infiltration. Note that some of the estimated infiltration values are negative. While we do not feel that groundwater was seeping into the pond as these would imply, the values were left in to give a sense of the uncertainties associated with this approach. During the first 8 months the pond was in use, nearly all loss from the pond was by evaporation. From 8 months to 16 months infiltration was the dominate outflow mechanism. After 16 months, infiltration decreases substantially and evaporation again becomes the dominant process in water loss.

The data suggest that when the pond was first being filled, unsaturated conditions beneath the pond floor limited vertical movement of water. Eventually saturation was achieved, preferred flow paths developed, pond stage increased due to CBM-water production, and sufficient Ca/Mg salts were present to keep the SAR of the percolating water low (preventing the deflocculation of clays). During this time the relatively high infiltration rates were seen. Once Ca/Mg salts became flushed from the pond floor the clays dispersed due to the high-SAR of the percolating water, and infiltration was substantially reduced. Once discharge to the pond ceased it slowly dried by evaporation.

Vertical hydraulic conductivity (K_z), averaged over the area of the pond floor, can be calculated on a monthly basis, using the results of the water budget and the gradient between the piezometer and the pond water levels. The water levels and the results of the K_z calculations are listed in Table 1 and shown graphically on Fig. 6. The calculation is based on the assumptions that all seepage from the pond was vertical and that seepage occurred uniformly over the entire saturated area of the pond floor.

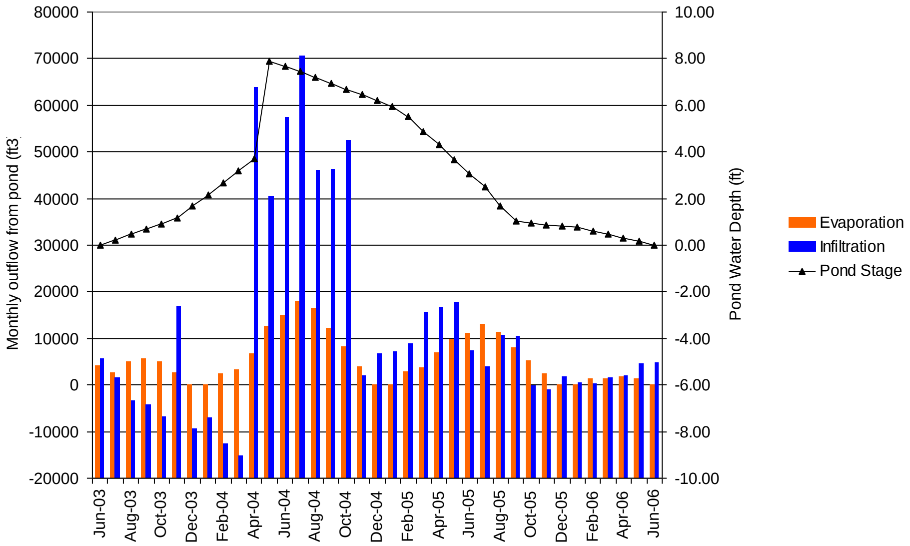

Figure 5. Outflow from the pond was through evaporation and infiltration

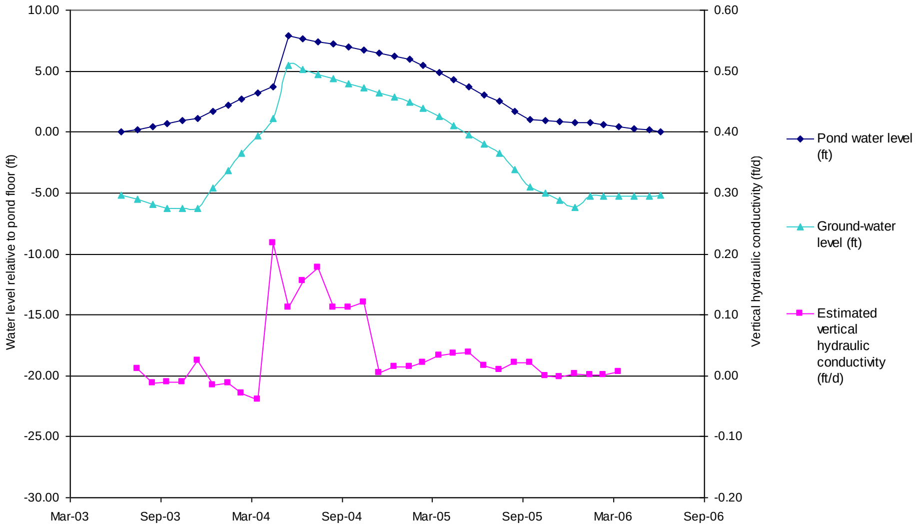

Figure 6. The vertical hydraulic conductivity, as estimated from the water budget, shows a marked decrease after extended exposure to the high-SAR produced water.

The calculated K_z values mirror the infiltration rates, being low initially, then increasing to between 0.1 and 0.2 ft/day (0.03 and 0.06 m/day) for a period of 7 months. After that time K_z values decrease to near the initial rates. As was noted in the water-budget discussion, it appears that through cation exchange Na in the water drove dispersion of clay in the pond floor once Ca/Mg salts were no longer available to off-set the effects of the Na. This results in plugging of pore throats and decreases K_z.

Additional evidence of cation exchange in the pond floor is seen in strontium isotope data. Strontium data from water samples from the pond and from wells completed beneath the pond were evaluated in an effort to document the flow path of the infiltrating water and for evidence of ion-exchange reactions on the pond floor. Strontium isotopes have been shown to be effective tracers of water mixing in some situations (Frost and Toner, 2004). Water obtains Sr from the aquifer material it interacts with, so will therefore have as great a range of Sr isotope ratios as does geologic material. Therefore, the ratio of the radiogenic isotope ^{87}Sr to the common isotope ^{86}Sr ($^{87}Sr/^{86}Sr$) should be a good candidate for fingerprinting water and tracing the mixing of water originating in different aquifers. Water originating in deep coal aquifers, such as that discharged at the surface during CBM production, has a good chance of having a measurably different Sr isotope ratio from the surface water and near surface aquifer water with which it is interacting. This is true in the Coal Creek CBM off-channel pond where the CBM produced water has a Sr isotope ratio of 0.7118 while the local water has a higher $^{87}Sr/^{86}Sr$ ratio of 0.7140.

However, Sr isotopes are not an immutable "fingerprint" because the measured Sr isotope ratio of CBM water can be changed through dissolution of Sr bearing salt with a different $^{87}Sr/^{86}Sr$ ratio and through cation exchange with Sr on local soil clays (Johnson and DePaolo, 1997a). The usefulness of Sr isotopes in environmental studies depends upon the Sr concentration of the water of interest, in this case the introduced CBM water, and the concentration of Sr derived from dissolution of salt. If too much local Sr from the dissolution of salt is introduced to the water, the local Sr isotope ratio will overwhelm the $^{87}Sr/^{86}Sr$ ratio of the introduced CBM water making tracing the flow path of the CBM water using Sr isotopes difficult to impossible.

At the Coal Creek Site, the Sr isotope ratio of the CBM input water is quickly overwhelmed by the Sr isotope ratio of the local salts. The Sr isotope ratio of water sampled from a well screened 23.5 ft (7 m) below the floor of the pond is already indistinguishable from the local Sr ratio. However, the rate of change of the Sr isotope ratio and changes in the Sr concentration can also be indicators of geochemical processes (Johnson and DePaolo, 1997b). Samples collected just above the pond floor show a slow upward trend in Sr isotope ratio while also decreasing in Sr concentration over the 20 month sampling period between December 2003 and July 2005 (Fig. 7). These trends continued even after the CBM water was no longer being discharged into the pond. Changing Sr isotope ratio without a corresponding increase in concentration is not likely due to dissolution of salts, but is probably due to continued cation exchange with pond floor clays which can change the Sr isotope ratio without increasing the concentration of Sr. The decreasing concentration of Sr may be due to precipitation of Sr salts from the pond water. CBM water, due to its bicarbonate composition, is often oversaturated with respect to carbonates (Patz et al. 2006; McBeth et al. 2003); including Sr carbonate (strontianite). As the CBM water interacts with the atmosphere, the pH of the water increases due to degassing of CO_2. This more alkaline water cannot hold as much Sr carbonate in solution, resulting in additional precipitation of Sr and the decreasing Sr concentrations as seen in Fig. 7.

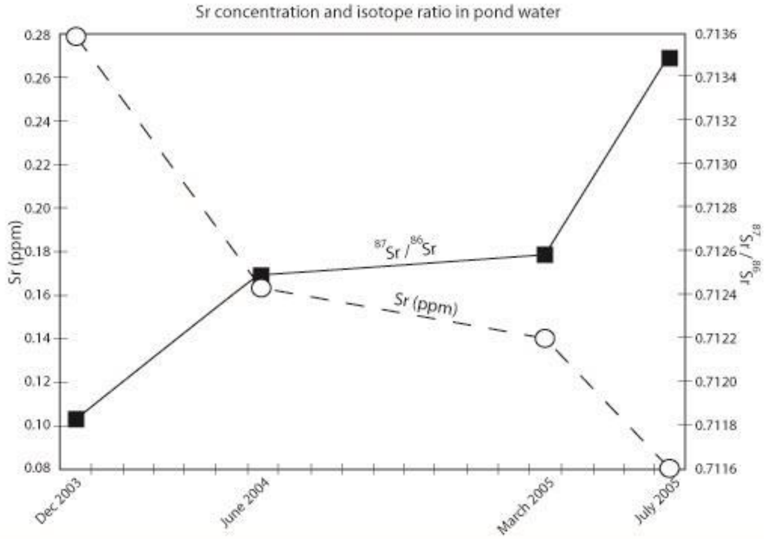

Figure 7. Strontium concentration (open circles, dashed line) and strontium isotope ratio (solid squares, solid line) with time for samples collected just above the floor of Coal Creek Pond. CBNG produced water strontium isotope ratio and concentration are nearly identical to the December 2003 pond sample.

Conclusion

Significant volumes of ground water are produced in association with coalbed-methane production in the Powder River Basin in Montana and Wyoming. This water must be managed in a manner that conserves it as a water resource for the semi-arid agricultural area of southeastern Montana and northeastern Wyoming and that is economical for the producing companies. Infiltration ponds are one water management option. They require a low initial investment and can help recharge the shallow ground-water system. However, Na in the produced water can cause clay dispersion in the pond floors through ion exchange. At some sites this may cause rates of infiltration to decrease with time.

At the Coal Creek site, about one-third of the water entering the pond was lost to evaporation and the remaining two-thirds infiltrated in to the shallow ground-water system. After the pond floor and underlying materials became saturated, vertical hydraulic conductivity was between 0.1 and 0.2 ft/day (0.03 and 0.06 m/day). However, it appears that this rate decreased substantially when Ca/Mg salts became flushed from the system and clays became deflocculated due to the high-SAR produced water. Strontium concentrations and isotope data support the suggestion that ion exchange between the water and the clay in the pond floor drives the dispersion of the clay and resultant reduction in infiltration. There is, however, a possible advantage in the reduced K_z, in that salts that have been mobilized by the infiltrating water may be sequestered. Saturated flow is needed to transport salts in the subsurface. Once the pond floor is sealed, there is very little chance for future infiltration along the same flow path that could transport those salts further. When there is not saturated flow the water evaporates in the subsurface and the salts are sequestered.

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