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Full Length Research Paper

A trial to determine the impact of soil washing on coal seam gas (CSG) dam sediments in Queensland

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Extracting coal seam gas (CSG) is becoming increasingly common in Australia and throughout the world. With the number of wells in Queensland alone increasing from 10 in 1995 to 4,484 by 2013 and 20,000-40,000 more expected to be drilled in the next 20 years, the production of methane from CSG is forecast to become one of Australia's largest export commodities within the next decade. There is, however, growing disquiet about the potential for CSG to negatively impact the environment because it generates a number of gaseous, liquid and solid waste streams, the composition of which are largely unknown. CSG waste streams include fugitive emissions, drilling mud, chemical fracking fluids, produced chemical fracking fluids, and produced water and brines, some of which are settled water and brines, some of which are settled into large evaporation dams to form sediments. Moreover, minimal data on the chemical and physical properties of these various waste streams resulting from rigorous environmental research have been published or made publicly available, adding to society's growing concern for CSG as an environmentally sustainable approach to extracting gas from coal. For this reason, the present study examines the chemical properties of two types of CSG dam sediment from the Bowan Basin in Queensland, and investigates the role that conventional soil washing might have in converting these low-level contaminated sediments into a "clean soil" which can be applied in on-site, beneficial reuse projects; the chemical properties of the resultant flushing solutions are also examined. The study found the majority of components in CSG dam sediments are benign, and soil washing removes or partially removes most inorganic contaminant species from CSG dam sediments; the study also found that these contaminants were mostly transferred to the flushing solution, which can be treated separately and potentially reused for livestock drinking water or irrigation water or recycled into the operating circuit.

Key words: Coal seam gas, CSG, soil washing, sediment, flushing solution.

INTRODUCTION

Coal seam gas (CSG) extraction is an industrial process developed to produce methane (CH_4) from uneconomical coal reserves. CSG uses a method called "cleat pressure drawdown" to depressurize and thereby liberate gas from underground coal formations using large quantities of pumped freshwater. According to industry predictions, by accessing this "unminable" coal CSG has the potential to increase global coal reserves by 600 billion tonnes or 70%, with India alone planning to access 350 billion tonnes of gas using non-conventional means, including

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CSG (World Energy Council, 2013: 1.7). As a consequence, the scale and volume of gas production from CSG in Australia has increased exponentially over the last ten years. For example, the number of wells across Queensland has increased from 10 in 1995 to 4,484 in 2013, with an additional 20,000-40,000 wells expected to be drilled in the next 20 years (Lloyd-Smith and Senjen, 2011, citing Queensland Government forecasts); as a consequence, production of methane from CSG and other gas commodities are expected to become one of Australia's largest exports within the next decade (EnergyQuest, 2009).

Queensland's four main gas fields in the Bowan, Surat, Galilee, and Clarence-Moreton Basins together generated a combined gas production of 4 PJ in 1999, 63 PJ in 2006, and 264 PJ in 2013 (Department of Natural Resources and Mines, 2014: 1). Along with other forms of liquefied natural gas (LNG) generated by conventional processes and non-conventional processes, such as underground coal gasification (UCG), CSG will be routed via the $70 billion Curtis Island gas terminal in Gladstone and newer hubs for export to overseas (mostly Asian) markets, although recent reports suggest that some CSG wells are underperforming expectations (Chambers, 2013). Of the 4,484 CSG production wells currently generating methane in Queensland, 68 use hydraulic fracturing (or "fracking") to liberate gas from coal, but none of the 230 wells in New South Wales employs the practice. This finding is relevant to the case made against CSG, because fracking is considered a significant contributor to environmental pollution, particularly of groundwater (Lloyd-Smith and Senjen, 2011), and benzene, a known mutagen and carcinogen, has been found in the produced water of some CSG operations (Cubby, 2010).

Along with the extraction of commercial gas, CSG operations also generate a range of waste byproducts, including fugitive gas emissions (Day et al., 2103, found a CSG operation in Queensland inadvertently released between 13 tonnes and 58 tonnes of CH_4 per year, 17 tonnes per year of which could still be measured 3.0 km from the site), drilling mud, wastewater (or "produced water" in the language of the industry), and brine. For example, while it differs from well-to-well, an average CSG well will generate between 3,000 and several hundred thousand litres of wastewater per day depending on coal seam formation (CSIRO, 2012: 1); as a consequence, a total of 16.9 GL of wastewater was generated by Queensland's CSG wells in 2012 (Department of Natural Resources and Mines, 2014: 1). Problems associated with so-called "overburden fracturing", that is, when the ground surface above a CSG well subsides, have also been reported. About 3 to 5% of CSG wastewater by volume is actually solids, typically present in the liquid fraction as suspended, colloidal particles or dissolved solids; most of these solids are composed of indigenous alkanic hydrocarbons and/or "salty brines", which do not form part of the gas fraction. Thus, a minimum of approximately 480 million tonnes of brine is generated each year in Queensland; these brines are generally settled in holding ponds or evaporation dams located contiguously to clusters of wells (the footprint of dams can be up 100 ha in area). Wastewater is typically allowed to either evaporate, be recycled to livestock drinking water or irrigation water, or be used as cooling water after treatment with reverse osmosis; brines can be disposed to regulated landfill (Egan, 2012). Not a lot of information has been written about the chemical properties of wastewater generated by CSG (e.g., CSIRO, 2012); what has been written typically focuses on the potentially harmful health effects of chemicals used in fracking and their likelihood of polluting groundwater. For example, Colburn et al. (2011) revealed that of the 632 documented chemicals found in 944 fracking fluids, 353 had been assigned a Chemical Abstract Service (CAS) tracking number, 75% of which can damage the skin, eyes and respiratory and gastrointestinal systems, at least 40% can affect the brain and central nervous system, immune system and cardiovascular system, and 25% can cause cancer.

However, the systematic study of groundwater and its hydrogeology are themselves fraught with sometimes insurmountable hurdles, not the least of which is any attempt to understand the fluid dynamics and chemical behaviour of interactions occurring between 300 to 1,000 m underground. The fact that industry has not always been entirely forthcoming about the chemical components of fracking fluids or other waste streams generated by CSG only adds to society's concerns and suspicions (Gottlieb, 2013). What role environmental remediation interventions, such as soil washing and partitioning, might play in addressing organic and inorganic contaminant species in CSG wastewater and sediments, should they exist, has yet to be examined.

Washing contaminated soils and sediments has been well documented (Abumaizar and Smith, 1999; Dermont et al., 2008; Mann, 1999) and is particularly common in mine site rehabilitation (Moutsatsou et al., 2006). Soil washing is an *ex-situ* remediation process which involves mixing solids with freshwater in a low-impact agitator, thereby liberating or "partitioning" contaminants from soil. Once the washing cycle has occurred, treated solids are settled and the so-called "flushing solution" decanted for discharge or recycling, in theory leaving behind clean soil. This practice has become more widespread in commercial remediation applications in the last ten years, particularly in Europe where the greatest expertise resides, however soil washing is rarely undertaken in Australia.

Soil washing is based on the principle that an organic or inorganic contaminant will bind to the soil's fine particles, which in turn bind to coarser particles, and thus by separating the course fraction from the fine fraction using agitated fresh water, contaminants along with the using agitated fresh water, contaminants along with the finest soil fractions can be partitioned from the soil, thereby liberating contaminants from the course fraction. This process then allows the separated flushing solution to be treated and discharged or recycled in further washing cycles, leaving behind a remediated course soil fraction which can be reused as backfill or, as is intended in CSG applications, integrated into beneficial reuse programs to rehabilitate disturbed land. Some soil washing techniques also use surfactants or other chemical additives to aid in the liberation of contaminants (Chu and Chan, 2003; Torres et al., 2012), and novel agitation mechanisms, including jet reactions and ultrasonic washing (Feng et al., 2001), have been deployed.

However, to this author's knowledge, soil washing has never been applied to CSG sediments, and fundamental questions such as ease of application, sediment treatment outcomes, role of surfactants, and other basic scientific data are lacking from the literature. Moreover, even the most basic information related to the chemical and physical properties of CSG waste sediments are all but non-existent. For these reasons, the present study asked four research questions: 1) What are the chemical properties of CSG dam sediments; 2) does soil washing (with or without surfactants) reduce contaminant species (if any) in CSG dam sediments to a point where sediments can be reused as "clean soil"; 3) what are the chemical properties of flushing solutions after partitioning; and 4) do flushing solutions generated from the washing of CSG sediments meet standards for water reuse as livestock drinking water or irrigation water? Exploring methods which might allow for beneficial reuse of sediment as clean soil is aligned to the Queensland Government's priority to decommission CSG evaporation dams, although the government only identifies "creating saleable salt", injecting sediments into underground voids, or disposing it to regulated landfill in their "range of options" (2012: 5).

METHODS

Two x 33 kg samples of CSG evaporation dam sediments were collected from dam sites in the Bowen Basin, central Queensland. The two sediment samples were labelled 1 and 2, with sample 1 collected from about 500 mm under water in an operational dam, and sample 2 from a decommissioned, dewatered dam in which sediments had dried and oxidized naturally; sample 1 therefore was an un-oxidized sediment, whereas sample 2 was an oxidized and naturally weathered sediment. Visual inspection of sample 1 indicated a fine grained (1.0 to 2.0 mm), spadable, greyish sediment with brown-grey stratigraphy (possibly sand) with no obvious smell of hydrocarbons or phenols; on a scale of 0 to 5, with 5 being the most objectionable, the sample's odour was rated 0. Inspection of sample 2 also indicated a fine-grained, spadable, grayish sediment with a blue-grey stratigraphy, but this sample appeared to contain fibrous vegetable matter (possibly grass); similarly, sample 2 had no obvious smell of hydrocarbons or phenols, but a sweet odour like potatoes, which was rated between 0 to 1.

In order to answer research question 1, 1 kg subsamples of both samples 1 and 2, labelled 1A and 2A, were sent to a certified laboratory in Brisbane for analysis of the following: pH; electrical conductivity (EC); total calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and chloride (Cl); total alkalinity (the sum of bicarbonate and carbonate alkalinity); exchangeable or soluble calcium, magnesium, potassium, and sodium; cation exchange capacity (CEC is the number of exchangable cations that the sediment is capable of holding, at a given pH, which are available for exchange with the flushing solution); sodium adsorption ratio (SAR is a measure of the suitability of water for use in agricultural irrigation as determined by concentrations of solids dissolved in the water); total metal concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn); leachable metal concentrations of the same heavy metals; benzene, toluene, ethylbenzene, and xylene (BTEX); organochlorine pesticides; polycyclic aromatic hydrocarbons (PAH); total petroleum hydrocarbons (TPH); and ammonia.

The two samples were divided into two x 2 kg subsamples, labelled 1B and 1C for sample 1 and 2B and 2C for sample 2. In order to answer research question 2, these four subsamples were subjected to the following soil washing regimes. Subsample 1B was mixed with 5.0 L of fresh water without a surfactant (ratio 1:2.5 sediment:water) for 15 minutes using a slow electric mixer; the solids were separated by passing the mixture through a 100 micron geotextile membrane and retaining the flushing solution as (a); subsample solids were rewashed a second time with another 5 L of fresh water for 15 minutes using the same method; the sediment-water mixture was again dewatered using the geotextile membrane and the flushing solution decanted and retained as (b); the solid fraction of subsample 1B was retained for analysis; flushing solutions (a) and (b) were mixed together and retained for analysis as FS1B.

The second subsample 1C was washed with 4.0 L of fresh water using 40 ml (1%) of sodium lauryl sulfate ($CH_3[CH_2]_{11}OSO_3Na$) as a surfactant (ratio 1:2 sediment:water) for 15 min; the solids were separated by passing the mix through a 100 micron geotextile membrane and retaining the flushing solution as (a); subsample solids were rewashed a second time with another 4.0 L of fresh water for 15 min using the same method, but without the surfactant; the sediment-water mix was again dewatered using the geotextile membrane and the flushing solution decanted and retained as (b); the solid fraction of subsample 1C was retained for analysis; flushing solutions (a) and (b) were mixed together and retained for analysis as FS1C. Subsamples 2B and C were subjected to the same soil washing regimes as subsamples 1B and 1C, and resulted in flushing solutions FS2B and FS2C.

For the purposes of this study, the term "clean soil" referred to washed CSG dam sediments which conform to these criteria: 1) the sediments would be comparable to profiles of clean "background soils" derived from samples taken in the vicinity of the evaporation dams where samples 1 and 2 were collected (determined by data supplied to the author by the CSG dam operator); and 2) contaminants in the sediments would be at or below levels set by the Australian Standard AS-4454 for soil suitable as a "soil conditioner" (Dorahy et al., 2007).

To answer research question 3, flushing solutions which resulted from these four soil washing regimes (that is, FS1B, FS1C, FS2B and FS2C) were analysed for the following: pH; EC; total dissolved solids (TDS); total Ca, Mg, K, Na, sulfate (SO_4), chloride (Cl), and flouride (Fl); hardness; hydroxide alkalinity, total carbonate alkalinity, total bicarbonate alkalinity, and total alkalinity; and total As, Cd, Cr, Cu, Pb, Hg, Ni, and Zn. It should be noted that because saline water matrices are prone to analytical interference due to the presence of high levels of TDS (the NATA-certified laboratory used in this study applies a 2,000 mg/L cut-off limit for TDS) and individual cations and anions; for this reason, flushing solution subsamples FS1C, FS2B and FS2C required dilution prior to

Table 1. Chemical analysis of sediment sample 1 before soil washing (1A) and after two soil washing methods (1B and 1C), with percent changes between 1A and 1B and between 1A and 1C, background soil, and AS-4454.

Parameter	1A	1B	Percent change between 1A and 1B	1C	Percent change between 1A and 1C	Background soil	AS-4454
pH	9.8	10.0	—	10.0	—	8.2	5.0-7.5
EC (mS/cm)	2.1	0.46	78↓	0.2	90↓	0.84	No limit
Ca (mg/kg)	<10†	<10†	—	<10†	—	7,320	No limit
Mg (mg/kg)	<10†	<10†	—	<10†	—	2,680	No limit
K (mg/kg)	80	10	88↓	<10†	100↓	1,390	No limit
Na (mg/kg)	4,090	620	85↓	370	91↓	120	<10,000
Cl (mg/kg)	5,400	200	97↓	50	99↓	<10†	No limit
Total alkalinity as $CaCO_3$ (mg/kg)	1,320	1,180	11↓	673	50↓	230	TBD‡
Exchangeable Ca(meq/100 g)	12	10.5	13↓	8.1	34↓	22.8	No limit
Exchangeable Mg (meq/100 g)	2.6	1.5	43↓	1.0	62↓	6.2	No limit
Exchangeable K(meq/100 g)	0.8	0.3	63↓	0.1	88↓	1.0	No limit
Exchangeable Na (meq/100 g)	9.6	2.5	74↓	1.2	88↓	<0.1	No limit
CEC (meq/100 g)	25	15	40↓	10	59↓	30	No limit
SAR (meq/100 g)	189	77	60↓	50	74↓	—	No limit
As (mg/kg)	7.0	5.0	39↓	<5.0†	100↓	6.0	20
Cd (mg/kg)	<1.0†	<1.0†	—	<1.0†	—	<1.0	3.0
Cr (mg/kg)	20	14	30↓	12	40↓	20	400
Cu (mg/kg)	17	9.0	48↓	6.0	65↓	22	200
Pb (mg/kg)	11	9.0	19↓	<5.0†	100↓	19	1.0
Hg (mg/kg)	<1.0†	<1.0†	—	<0.1†	—	<1.0	60
Ni (mg/kg)	12	6.0	50↓	4.0	67↓	17	200
Zn (mg/kg)	24	10	59↓	7.0	71↓	19	250
Average percent change for K, Na and Cl	—	—	90↓	—	97↓	—	—
Average percent change for metals	—	—	41↓	—	74↓	—	—

† Below level of detection; ‡ to be determined, because AS-4454 does not have a limit on total alkalinity but requires a subjective judgment based on pH.

analysis. To answer research question 4, this study used ANZECC (2000) guidelines for livestock drinking water and irrigation water.

RESULTS

Tables 1 and 2 present the analytical findings of subsamples 1A and 2A related to research question 1. As no evidence of leachable metals, BTEX, pesticides, PAH, TPH or ammonia was found in either subsample 1A or 2A, these data have not been included in Tables 1 or 2, with all parameters below the limits of detection of 0.1 mg/L for leachable metals, 0.2 mg/kg for BTEX and ammonia (as NH_3), 0.5 µg/kg for pesticides, 0.004 µg/kg for PAH, and 3.0 mg/kg for TPH.

As shown in Table 1, subsample 1A had significantly higher pH, EC, and concentrations of sodium and chloride than background soil, although calcium, magnesium and potassium were significantly lower than background soil; most other variations between 1A and background levels follow from these concentrations of sodium and chloride, for example total alkalinity. Metal concentrations were almost identical in both subsample 1A and background soil.

Similarly, subsample 2A had a significantly higher pH and EC, and higher concentrations of sodium and chloride than background soil, although Ca, Mg and K were significantly lower than background soil, as was the case for sample 1. Metal concentrations were almost identical in both sample 2A and background soil. When AS-4454 standards are applied to subsamples 1A and 2A, these CSG sediments would not be considered acceptable for soil conditioning or on-site rehabilitation due to higher than allowable pH in both subsamples, and lead in 1A and lead and Na in 2A.

Results for soil washing regimes 1B and C are shown in Table 1 as compared with both the unwashed subsample 1A and background soil and AS-4454 guidelines. In all cases except pH, all parameters decreased when comparing 1A to 1B and 1A to 1C, with

Table 2. Chemical analysis of sediment sample 2 before soil washing (2A) and after two soil washing methods (2B and C), with percent changes between 2A and B and between 2A and C, background soil, and AS-4454.

Parameter	2A	2B	Percent change between 2A and B	2C	Percent change between 2A and C	Background soil	AS-4454
pH	10.0	10.1	—	10.1	—	8.1	5.0-7.5
EC (mS/cm)	9.4	1.4	86↓	1.7	82↓	0.17	No limit
Ca (mg/kg)	10	<10†	100↓	<10†	100↓	6,600	No limit
Mg (mg/kg)	<10†	<10†	—	<10†	—	1,840	No limit
K (mg/kg)	340	40	89↓	60	83↓	980	No limit
Na (mg/kg)	16,100	1,900	88↓	3,150	81↓	170	<10,000
Cl (mg/kg)	19,900	1,670	92↓	3,150	85↓	<10†	No limit
Total alkalinity as $CaCO_3$ (mg/kg)	6,290	1,620	75↓	2,080	66↓	345	TBD‡
Exchangeable Ca (meq/100 g)	14.7	14.6	0	14.9	2↑	24.6	No limit
Exchangeable Mg (meq/100 g)	0.8	0.7	13↓	0.8	0	5.3	No limit
Exchangeable K (meq/100 g)	0.9	0.5	45↓	0.8	12↓	0.6	No limit
Exchangeable Na (meq/100 g)	7.3	3.9	47↓	7.8	7↑	0.1	No limit
CEC (meq/100g)	24	20	17↓	24	2↑	30.7	No limit
SAR (meq/100g)	931	173	82↓	255	83↓	—	No limit
As (mg/kg)	<5.0†	<5.0†	—	<5.0†	—	<5.0†	20
Cd (mg/kg)	<1.0†	<1.0†	—	<1.0†	—	<1.0†	3.0
Cr (mg/kg)	11.1	4.0	64↓	6.0	46↓	6.0	400
Cu (mg/kg)	10	<5.0†	100↓	5.0	50↓	11	200
Pb (mg/kg)	10	<5.0†	100↓	6.0	40↓	10	1.0
Hg (mg/kg)	<1.0†	<1.0†	—	<1.0†	—	<1.0†	60
Ni (mg/kg)	6.0	<2.0†	100↓	2.0	66↓	6.0	200
Zn (mg/kg)	21	<5.0†	100↓	8.0	62↓	13	250
Average percent change for Ca, K, Na and Cl	—	—	92↓	—	87↓	—	—
Average percent change for metals	—	—	93↓	—	53↓	—	—

† Below level of detection; ‡ to be determined.

total K, Na and Cl decreasing by an average of 90% for 1B and 97% for 1C (neither sample contained Ca or Mg). Similarly, total metals decreased by an average of 41% for 1B and 74% for 1C, indicating that the addition of a surfactant in soil washing improved metal removal efficiencies from CSG dam sediments. However, lead only decreased by 19% in 1B although by 100% in 1C; while the <5.0 parts per million observed for 1C may mean that lead concentrations were below the AS-4454 guideline, with a detection limit of 5.0 mg/kg and a guideline of <1.0 mg/kg, it is not possible to determine whether lead levels in 1C actually met the clean soil criterion or not. The pHs of washed sediments from both 1B and C were the same as 1A, and do not meet the criteria for clean soil when compared to either background soil or AS-4454 guidelines.

Results for soil washing regimes 2B and C are shown in Table 2 as compared with both the unwashed sub-sample 2A and background soil and AS-4454 guideline. In all cases except pH and exchangeable Ca, NA and CEC, which increased negligibly, analytes decreased when comparing results of 2A to B and 2A to C, with total Ca, K, Na and Cl decreasing by an average of 92% for 2B and 87% for 2C (neither sample contained Mg). Similarly, total metals decreased by an average of 93% for 2B and 52% for 2C, indicating that while soil washing removed metals from sediment, the addition of a surfactant did not improve metal removal efficiencies, which was the opposite finding to sample 1. Also in reverse of sample 1, lead decreased by 100% in 2B but only 40% for 2C; for reasons noted above, it is unclear whether lead levels in 2B met the clean soil criterion or not due to limitations of detection in instrumentation. The pHs of washed sediment from both 2B and C were the same as 2A, and do not meet the criteria for clean soil when compared to either background soil or AS-4454 guidelines (Table 3).

SAR is used to determine the suitability of soil to

Table 3. Analysis of flushing solutions resulting from soil washing regimes FS1B, FS1C, FS2B and FS2C, compared to ANZECC guidelines for livestock drinking water and irrigation water.

Parameter	FS1B	FS1C	FS2B	FS2C	Livestock drinking water	Irrigation water
pH	8.9	9.1	9.1	9.2	‡	6.0-9.0
EC (mS/cm)	1.1	5.5	7.8	26	‡	0.95- 12.2*
TDS(mg/L)	754	3,610	5,070	16,900	<2,000	‡
Ca (mg/L)	<1.0[†]	2.0	3.0	4.0	1,000	‡
Mg (mg/L)	<1.0[†]	<1.0[†]	<1.0[†]	<1.0[†]	‡	‡
K (mg/L)	4.0	21	25	105	‡	‡
Na (mg/L)	223	1,180	1,730	7,300	‡	‡
SO_4 (mg/L)	21	23	23	72	1,000	‡
Cl (mg/L)	223	1,280	1,770	8,220	‡	<170-750**
Fl (mg/L)	<10[†]	<10[†]	<10[†]	13	‡	‡
Hardness (mg/L)	<1.0[†]	5.0	7.0	10	‡	‡
Hydroxide alkalinity (mg/L)	<1.0[†]	<1.0[†]	<1.0[†]	<1.0[†]	‡	‡
Carbonate alkalinity (mg/L)	52	210	315	998	‡	‡
Bicarbonate alkalinity (mg/L)	316	420	919	2,130	‡	‡
Total alkalinity (mg/L)	368	630	1,230	3,120	‡	‡
As (mg/L)	0.02	0.06	0.07	0.22	0.5	0.1-20[#]
Cd (mg/L)	0.0006	0.0005	0.0006	0.002	0.01	0.01-0.05[#]
Cr (mg/L)	0.39	0.28	0.25	0.86	1.0	0.1-1.0[#]
Cu (mg/L)	0.47	0.30	0.29	0.99	0.5	0.2-5.0[#]
Pb (mg/L)	0.35	0.39	0.34	1.4	0.1	2.0-5.0[#]
Hg (mg/L)	<0.0001[†]	<0.0001[†]	<0.0001[†]	<0.0001[†]	<0.002	<0.002[#]
Ni (mg/L)	0.35	0.15	0.15	0.51	1.0	0.02-2.0[#]
Zn (mg/L)	0.56	0.42	0.37	1.3	20	2.0-5.0[#]

[†] Below level of detection; [‡] no guideline; * EC can range from a maximum of 0.95 mS/cm for salt intolerant, sensitive species, such as apple, to 12.2 mS/cm for highly salt-tolerant species, such as Rhodes grass; an EC above 12.2 mS/cm is considered too saline for plant growth (ANZECC, 2000, p. 4.2-7); ** Cl levels range from a maximum of 170 mg/L for sensitive species, such as citrus and grape, to 750 mg/L for more tolerant species, such as cauliflower (ANZECC, 2000, p. 4.2-10); [#] lower concentrations in the range indicate acceptable heavy metal concentrations in "long-term" applications of irrigation water, and higher concentrations indicate acceptable heavy metal concentrations in "short-term" applications of irrigation water.

receive irrigation water by measuring the relative concentrations of Na to Ca and Na to Mg; SAR is therefore an important measure when determining the suitability of soil for revegetation, but is less important when considering general land reclamation and rehabilitation. The absence of SAR data for background soil means there is no benchmark against which to compare washed sediments, although higher concentrations of Ca, Mg and K and lower concentrations of Na and Cl suggest background soil in the vicinity of the CSG dams is probably also saline, but not sodic. Using a general SAR calculation (Na/√Ca+Mg/2, from ANZECC, 2000: 4.2-4.6), the SAR of sample 1 background soil is 1.7 meq/100 g and sample 2 background soil is 2.6 meq/100 g, indicating that subsamples 1B, 1C, 2B and C are unsuitable as revegetation media, except in the most salt-tolerant cases. This conclusion is confirmed when comparing CEC and SAR to Cl concentrations in both cases.

Analyses of the flushing solutions generated from regimes FS1B, FS1C, FS2B and FS2C are shown in Table 3 and compared with ANZECC guidelines for livestock drinking water and irrigation water. The pH of all four flushing solutions are the same, and all parameters for use of the flushing solutions as drinking water for livestock, except TDS in subsamples FS1C, FS2B and FS2C, and lead in all subsamples, have been met. While levels of lead >0.1 mg/L may be hazardous to animal health, ANZECC guidelines state that acceptable levels of lead depend on the type and age of animals drinking the water, and therefore it may be possible that lead concentrations in subsamples FS1B, FS1C and FS2B (0.35, 0.39, and 0.34 mg/L respectively) meet acceptable livestock drinking water quality, although subsample FS2C at 1.49 mg/L is unlikely to do so.

Subsample FS1B meets, and subsamples FS1C, FS2B and FS2C almost meet, the pH criteria for irrigation water, however only subsample FS1B meets the Cl criteria for Cl-tolerant species, with subsamples FS1C, FS2B and FS2C significantly higher than allowable limits, and none of the subsamples meet the criteria for EC. ANZECC guidelines for heavy metals in irrigation water provide a range of acceptable limits, depending on whether the irrigation water is to be applied over a longer or shorter timeframe, with lower limits allowed when water is applied over a longer period and the reverse when applied over a shorter period. From these criteria, it can be seen: As concentrations in FS1B, FS1C and FS2B would be acceptable for long-term application, but FS2C would only be suitable for short-term application; Cr, Cu and Ni concentrations in all flushing solution subsamples would be acceptable only for short-term application; and Cd, Pb, Hg and Zn concentrations in all subsamples would be acceptable for both short- and long-term application of flushing solutions as irrigation water.

Conclusion

The Queensland Government has recognized that CSG sediments must be managed sustainably, and where possible its highest priority is to treat and beneficially reuse sediments; untreated disposal of sediments is considered a solution of “last resort” (Department of Environment and Heritage Protection, 2012). Therefore, any attempt to treat dam sediments using soil washing and partitioning would be considered worthwhile. However, in this study, soil washing was only partially effective in converting low-level contaminated dam sediments into “clean soil” (with the role of a surfactant indeterminate), and flushing solutions did not meet the standards required for use as either livestock drinking water or irrigation water.

In answer to research question 1, this study provides evidence that the CSG dam sediments tested in this experiment contain mostly “salts” and do not contain major contaminants of concern. For example, no evidence was found for the presence of benzene, PAHs (such as benzo(a)pyrene and naphthalene), petroleum hydrocarbons, pesticides or ammonia, and heavy metals were at generally low concentrations, although the presence of lead was concerning. The primary contaminants were inorganic cationic and anionic species, such as potassium, sodium and chloride.

From this data it is reasonable to conclude that soil washing went some of the way toward removing these contaminants from CSG dam sediments, thereby potentially allowing them to be re-classified as clean, useable soil suitable for on-site land reclamation, dam decommissioning and rehabilitation programs. While not all parameters conformed to the criteria set for this experiment, the washed sediments were generally significantly lower in most contaminant species as a result of soil washing. Therefore, research question 2 was partially answered in the affirmative, with the addition of a surfactant aiding removal efficiencies in one example but not in the other.

Similarly, this study provided evidence on the main contaminants in flushing solutions generated by soil washing of CSG dam sediments to answer research question 3, but showed the four flushing solutions generated in this experiment only partially met the criteria for use as livestock drinking water or irrigation water. These findings indicate that soil washing may be a viable method to recondition CSG dam sediments for on-site beneficial reuse when organic contaminants, such as petroleum hydrocarbons and benzene, are not present in the sediment profile. However, further research on the role of different surfactants, methods of soil washing (including volumes of water and water:sediment ratios), methods of mixing and agitation, energy consumption, and other physical and chemical parameters must be carried out before concluding that soil washing provides a viable, economical or operationally useful tool to treat CSG dam sediments and thereby convert them into a soil with beneficial reuse potential.

Conflict of Interest

The author has not declared any conflict of interest.

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REFERENCES

Abumaizar RJ, Smith EH (1999). Heavy metal contaminants removal by soil washing. J. Haz. Mat. 70(1-2):71-86.

Australian and New Zealand Environment Conservation Council (ANZECC)(2000). Guidelines for fresh and marine water quality, volume 1. Australian and New Zealand Environment Conservation Council (ANZECC), Artarmon, NSW.

Chambers M (2013). Export fears as gas wells fall short. The Australian, November 19, 2013.

Chu W, Chan KH (2003). The mechanism of the surfactant-aided soil washing system for hydrophobic and partial hydrophobic organics. Sci. Tot. Environ. 307(1-3):83-92.

Colburn T, Kwiatkowski C, Schultz K, Bachran M (2011). Natural gas operations from a public health perspective. Hum. Eco. Risk Pers. 17:1039-1056.

Commonwealth Scientific and Industrial Research Organisation (2012). Coal seam gas: Produced water and site management. Commonwealth Scientific and Industrial Research Organisation (CSIRO), Clayton South, Victoria.

Cubby B (2010). Origin stops coal seam gas drilling after chemicals found in water. The Sydney Morning Herald, October 21, 2010.

Department of Environment and Heritage Protection (2012). Coal seam gas water management policy. Energy Resources, Department of Environment and Heritage Protection, Brisbane, December 2012.

Department of Natural Resources and Mines (2014). Queensland’s coal seam gas overview. Department of Natural Resources and Mines, Report No. B/Brochures/CSG/CC13-PET001, Queensland Government, Brisbane, January 2014.

Day S, Dell’Amico M, Fry R, Javanmard H (2013). Preliminary field measurements of fugitive methane emissions from coal seam gas production in Australia. 14th International Conference on Coal Science and Technology, Pennsylvania, USA, September 29 – October 3:1445-1456.

Dermont G, Bergeron M, Mercier G, Richer-Laflèche M (2008). Soil washing for metal removal: A review of physical/chemical technologies and field applications. J. Haz. Mat. 152(1):1-31.

Dorahy CG, Pirie AD, Pengelly P, Muirhead LM, Chan KY, Jackson M, Smith A, Emery T (2007). Guidelines for using compost in land rehabilitation and catchment management. Department of Environment and Climate Change and Department of Primary Industries, New South Wales Government, Sydney.

Egan G (2012). CSG waste water trucked to Ipswich. The Queensland Times, June 13, 2012.

EnergyQuest (2009). Australia's natural gas markets: Connecting with the world. Part One: Essay, EnergyQuest, Adelaide, SA.

Feng D, Lorenzen L, Aldrich C, Maré PW (2001). *Ex-situ* diesel contaminated soil washing with mechanical methods. Min. Eng. 14(9):1093-1100.

Gottlieb B (2013). Hydraulic fracturing: How great is the risk to health? Environmental Health Policy Institute, Physicians for Social Responsibility, June 2013.

Lloyd-Smith M, Senjen R (2011). Hydraulic fracturing in coal seam gas mining: The risks to our health, communities, environment and climate. National Toxics Network, Bangalow, NSW, July 2011.

Mann MJ (1999). Full-scale and pilot-scale soil washing. J. Haz. Mat. 66(1-2):119-136.

Moutsatsou A, Gregou M, Matsas D, Protonotarios V (2006). Washing as a remediation technology applicable in soils heavily polluted by mining-metallurgical activities. Chemosphere 63(10):1632-1640.

Torres LG, Lopez RB, Beltran M (2012). Removal of As, Cd, Cu, Ni, Pb, Zn from a highly contaminated industrial soil using surfactant enhanced soil washing. Phys. Chem. Earth. Parts A/B/C 37-39:30-36.

World Energy Council (2013). Coal: Strategic insight. World Energy Council, London, UK.