Journal of Hydrology 519 (2014) 1485–1492

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Prospecting for groundwater discharge in the canals of Bangkok via natural radon and thoron

Supitcha Chanyotha [a,*], Chutima Kranrod [a], William C. Burnett [b], Derek Lane-Smith [c], Jesse Simko [c]

[a] Department of Nuclear Engineering, Chulalongkorn University, Bangkok 10330, Thailand
[b] Department of Earth, Ocean & Atmospheric Science, Florida State University, Tallahassee, FL 32306, USA
[c] Durridge Co., Inc., 524 Boston Road, Billerica, MA 01821, USA

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 2 August 2014
Accepted 7 September 2014
Available online 16 September 2014
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Philippe Negrel, Associate Editor

Keywords:
Groundwater
Seepage
Radon
Thoron
Bangkok
Thailand

SUMMARY

We conducted surveys of several canals in Bangkok, Thailand using continuous measurements of naturally occurring ^{222}Rn (“radon”) and ^{220}Rn (“thoron”). Shallow groundwater seeping into these canals is an important pathway for contamination of surface waters. Radon, with a half-life (3.82 days) shorter than the suspected flushing time of the canals, is widely distributed throughout the waterway. It can thus be used to estimate discharge via a mass balance approach but cannot specify precisely where the discharge is occurring. Thoron, on the other hand, with its rapid decay (56 s half-life) will only occur very close to points of entry. Thus, if one detects thoron in the environment, there must be a source nearby – a good ‘prospecting’ tool. We found thoron spikes in Klong Bangkok Noi during a survey in August 2009. We repeated the same survey route in June 2013 and found essentially the same pattern of high thoron peaks (indicating points of discharge) adjacent to several temples along the canal. The connection to temples is thought to be a consequence of these structures being built on relatively higher ground and having sandy substrates.

1. Introduction

Research over the past several years has shown that submarine groundwater discharge (SGD) in the coastal zone is a significant water and material pathway from land to sea (Moore, 1996, 1999; Taniguchi et al., 2002; Slomp and Van Cappellen, 2004; Burnett et al., 2003, 2006). Much of the research performed over the past decade or so has relied on the use of natural radiogenic isotopes of radon and radium to assess the levels of groundwater discharge. Radon (^{222}Rn; $T_{1/2} = 3.84$ days) works well for this purpose because groundwater typically has activity levels 2–3 orders of magnitude above those of most surface waters. In addition to coastal zone studies, radon has also been applied to assess groundwater discharge into lakes (Schmidt and Schubert, 2007; Dimova et al., 2013), streams and rivers (Ellins et al., 1990; Cook et al., 2003, 2006; Mullinger et al., 2007), drainage canals (Burnett et al. (2010)) and other areas of groundwater–surface water interactions. Technological advances have made measurement of both radon and radium radionuclides much more efficient and convenient (Moore and Arnold, 1996; Burnett et al., 2001; Dulaiova et al., 2005).

Another isotope of radon, ^{220}Rn ($T_{1/2} = 56$ s), called “thoron” has also been applied for source identification purposes in a few situations including an old water supply system in New Jersey (Burnett et al., 2007). In that example buildup of scale on the inside of pipelines served to concentrate radium over many years and this produced an in situ “radon-generator” that led to higher activities of radon (both ^{220}Rn and ^{222}Rn) coming out of the pipes than was present in the source water. While there were relatively high activities of thoron detected in these old pipelines, its use for groundwater discharge studies has been limited because of the difficultly in measuring a nuclide with such a short half-life. However, there is an advantage in searching for thoron since if one detects it in the environment, there must be a source nearby. Because of its rapid decay, ^{220}Rn unsupported by its parent ^{224}Ra would essentially disappear in about 5 min. Thus, thoron is potentially an excellent prospecting tool. In the case of measurements in natural waters, sources of thoron (as radon) would likely indicate groundwater seeps although other possibilities exist such as accumulations of thorium-enriched minerals (e.g., monazite).

Dimova et al. (2009) completed a series of laboratory tests that demonstrated that thoron could, in fact, be measured in natural

---

[*] Corresponding author. Tel.: +66 2 218 6781; fax: +66 2 218 6780.
E-mail addresses: supitcha.c@chula.ac.th, supitchacu18@gmail.com (S. Chanyotha).

http://dx.doi.org/10.1016/j.jhydrol.2014.09.014
0022-1694/© 2014 Elsevier B.V. All rights reserved.

waters with the same equipment (Durridge RAD7) used for our radon measurements. We tested this approach in the field during a survey of a few canals off the Chao Phraya River (Bangkok, Thailand) in 2009 where we already had indications from earlier ^{222}Rn surveys that shallow groundwater was actively seeping into the canals (Burnett et al., 2009). While the thoron results were generally low, and in many cases not clearly above background, there were definite spikes in the data that appeared to be well above the background noise level (Chanyotha et al., 2010, 2011). We interpreted these spikes as indicating the locations where groundwater is seeping out into the surface waters of the canals. As expected, the thoron distribution differed markedly from the radon. These canals are suspected as having flushing times on the order of a few weeks so with a half-life of almost 4 days, radon is widely distributed away from the actual sources while thoron will only appear very close to any active seeps. Thus, while radon can be used for estimating the quantity of groundwater flow via a mass balance approach, thoron may be more useful for "prospecting" for specific sites of discharge.

We will show here that a very similar thoron distribution was observed during a repeat survey in one of the same canals, almost 4 years later. This supports the view that the results are indeed indicating sites of active groundwater discharge rather than just statistical aberrations of the detector background. We also introduce a new computational tool, the "Meaningful Thoron Threshold" that helps an investigator using a RAD7 radon analyzer to decide whether low thoron levels are real or a statistically expected outlier in the presence of spillover from higher energy events.

2. Study site

Bangkok, originally Khrung Thep ("City of Angels"), is the capital city and most important port of Thailand. After Burmese invaders destroyed the former capital of Ayutthaya in 1767, a temporary capital was established 30 km downstream at Thonburi. Fifteen years later, King Rama I decided to move his palace across to the eastern side of the river where it still stands. His decision to isolate the royal palace resulted in the construction of the first of many canals (called "klongs" locally) that later ran throughout the city. During the 19th Century, the system of canals was expanded, horseshoe bends in the Chao Phraya River ("The River of Kings") were cut off to shorten travel times and boats became Bangkok's main form of transport. The canal and river network stretched hundreds of kilometers and was the lifeblood of the city. Canals connected houses, public spaces and temples as well as serving as transport corridors for commercial goods. At one point there were more floating markets than markets on land.

As the economic center of Thailand, Bangkok has an extremely high population density (total population ~10 million). Although it is a major port, it is located some 40 km upstream from the Gulf of Thailand on the Chao Phraya River (Fig. 1). Beginning in the mid-19th century, roads were built to facilitate land travel, but the river remained the principal artery of communication and the man-made canals served as smaller streets leading into residential districts. Many canals continue to serve as main transport routes to this day.

3. Experimental

3.1. Radon and thoron surveys

We performed detailed surveys of several klongs on the western (Thronburi) side of the Chao Phraya River during the period August 25–27, 2009, towards the end of the wet season. The klongs (hereafter abbreviated as K.) surveyed included K. Daokhanang, K. Bangkok Yai, K. Bangkok Noi, and K. Mon (Fig. 1). We made continuous measurements of ^{222}Rn, ^{220}Rn, conductivity, temperature, GPS coordinates, and water depth while the boat traveled at a constant and slow speed (4–5 km/h) to enhance the spatial resolution. These results were reported in Chanyotha et al. (2011).

Both our ^{222}Rn and ^{220}Rn measurements during the surveys were made with a 3-detector continuous monitoring system similar to that described in Burnett et al. (2001) and Dulaiova et al. (2005). A submersible pump delivered near surface water to an air–water exchanger ("RAD-AQUA") on board the boat while a re-circulating stream of air was pumped through 3 RAD-7 radon detectors arranged in parallel for measurement. We used RAD7 detectors since they are portable, can run on batteries, and capable of measuring both radon and thoron continuously and simultaneously. Continuous monitoring of the water–air mixture in the exchanger via a temperature probe allowed for calculation of the radon solubility coefficients and thus conversion from radon-in-air to radon-in-water activities (Schubert et al., 2012). The ^{222}Rn activities were based on the number of counts in the "A" channel (^{218}Po) divided by the live time and sensitivity. While the RAD7 measures radon and thoron in air, all results reported here have been converted to activities in water.

In order to achieve the maximum spatial resolution for both radon and thoron, we used a protocol that provided a new reading every 5 min (in this mode the internal RAD7 air pumps will run continuously, which is necessary for thoron). We also ran the water pump as fast as possible (~6 L/min) to minimize decay during processing (Dimova et al., 2009). Our radon/thoron mapping system also incorporates integrated global positioning system navigation, depth sounding, in situ specific conductivity and temperature measurements via a Waterloo Scientific CTD. The CTD probe was attached to the harness of the submersible pump and recorded temperature and conductivity at 1-min intervals throughout the surveys.

The thoron results reported here were collected during both the 2009 and 2013 surveys in the "B" window (^{216}Po) of each RAD-7 and were corrected for the approximately 1.5% spectral spillover from the "C" window (^{214}Po) into the ^{216}Po area. We assumed for the purpose of this survey that the efficiency of thoron detection is half that for radon. The loss of thoron by decay during the travel time of the water from the point of sampling to the exchanger and then from the air phase in the exchanger to the RAD7 measurement chamber must be substantial. We included a factor to account for this decay but there is a large uncertainty associated with this estimate. However, we did make a concerted effort to maintain all relevant operating conditions, especially the water and air flow rates, uniform so we feel that the relative values reported for thoron are reasonably correct, at least within the same survey. Thus, the activity values reported for thoron are thus given as arbitrary yet relative units.

While it is possible to calibrate the RAD7 for thoron in air measurements, determinations in water have the additional uncertainty of the time it takes to introduce the thoron to the detector. In addition, absolute values would add little to the interpretations made here. In a previous study of thoron in old water supply systems, a calibrated system was used and absolute ^{220}Rn values reported. In that case absolute values were needed as part of the investigation (Burnett et al., 2007). Furthermore, the activities in that study were much higher than in the surface waters measured here and the water flow rates could be carefully controlled. Having an absolute sensitivity of the system would contribute little to the assessment of whether a thoron reading is meaningful or not. Calibration of the system would not change the level, in the air loop or in the water, at which we can confidently say we have a meaningful thoron reading (see next section). We just need to know if