Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-294
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 2 July 2018

Hydrology and Earth System Sciences
Open Access
Discussions

The importance of small artificial water bodies as sources of methane emissions in Queensland, Australia.

Alistair Grinham[1], Simon Albert[1], Nathaniel Deering[1], Matthew Dunbabin[2], David Bastviken[3], Bradford Sherman[4], Catherine E. Lovelock[5], Christopher D. Evans[6]

[1] School of Civil Engineering, The University of Queensland, Brisbane, 4072, Australia
[2] Queensland University of Technology, Institute for Future Environments, Brisbane, QLD, Australia
[3] Department of Thematic Studies–Water and Environmental Studies, Linköping University, Linköping, SE-58183, Sweden.
[4] CSIRO Land and Water, Canberra, 2601, Australia
[5] School of Biological Sciences, The University of Queensland, Brisbane, 4072, Australia
[6] Centre for Ecology and Hydrology, Environment Centre Wales, Bangor, LL57 2UW, UK

Correspondence to: Alistair Grinham (a.grinham@uq.edu.au)

Abstract. Emissions from flooded land represent a direct source of anthropogenic greenhouse gas emissions. Methane emissions from large, artificial water bodies have previously been considered, with numerous studies assessing emission rates and relatively simple procedures available to determine their surface area and generate upscaled emissions estimates. In contrast, the role of small artificial water bodies (ponds) is very poorly quantified, and estimation of emissions is constrained both by a lack of data on their spatial extent, and a scarcity of direct flux measurements. In this study, we quantified the total surface area of water bodies $< 10^5$ m^2 across Queensland, Australia, and emission rates from a variety of water body types and size classes. We found that the omission of small ponds from current official land-use data has led to an under-estimate of total flooded land area by 24%, of small artificial water body surface area by 57%, and of the total number of artificial water bodies by an order of magnitude. All studied ponds were significant hotspots of methane production, dominated by ebullition (bubble) emissions. Two scaling approaches were developed with one based on pond primary use (stock watering, irrigation and urban lakes) and the other using size class. Both approaches indicated that ponds in Queensland alone emit over 1.6 Mt CO_2-eq yr^{-1}, equivalent to 10% of the state's entire Land Use, Land Use Change and Forestry sector emissions. With limited data from other regions suggesting similarly large numbers of ponds, high emissions per unit area, and under-reporting of spatial extent, we conclude that small artificial water bodies may be a globally important 'missing source' of anthropogenic greenhouse gas emissions.

1 Introduction

Over the last 20 years greenhouse gas emissions studies from large, artificial water bodies such as water supplies or hydroelectric reservoirs have clearly demonstrated these are major sources of atmospheric methane (CH_4) emissions. Increasingly sophisticated reviews have explored the magnitude of their contribution to regional and global CH_4 budgets (St. Louis et al., 2000;Bastviken et al., 2011;Deemer et al., 2016). Much of the focus in reducing the uncertainty from this anthropogenic greenhouse gas source has focussed on the spatial and temporal variability in total emission rates and, in particular, the relative contribution of CH_4 bubbling (ebullition) directly from the sediment (Bastviken et al., 2011). To enable large-scale emissions estimates from larger, artificial waterbodies, relationships between eutrophication status and sediment temperature (Aben et al., 2017;Harrison et al., 2017) have been developed to predict both diffusive and ebullitive emission rates. However, in regional or global scaling of emissions it is important to examine the uncertainty in surface area (Chumchal et al., 2016) and the emission rates of all classes of artificial water bodies (Panneer Selvam et al., 2014). Given there are estimated to be 16 million artificial water bodies with a surface area less than 0.1 km^2 (Lehner et al., 2011), understanding the rates and variability in emissions from these flooded lands will be an important refinement to global CH_4 budgets.

The increasing urbanisation of society as well as the expansion of agriculture and commercial mining activities has resulted in a proliferation of small artificial water bodies in many parts of the globe (Renwick et al., 2005;Downing et al., 2006;Pekel et al., 2016). This is well illustrated by the example from the United States where artificial small water bodies increased from an estimated 20,000 in 1934 (Swingle, 1970) to over 9 million in 2005 (Renwick et al., 2005). These water bodies provide valuable services and are required to irrigate crops, provide water for farm stock, manage stormwater, offer visual amenity and recreational activities, and supply water for industrial processes (Fairchild et al., 2013). Small water bodies are often avian biodiversity hotspots, for example hosting an estimated 12 million water birds in a single catchment area in the Murray-Darling river system, Australia (Hamilton et al., 2017). However, the creation of water small artificial water bodies also represent a transformation of the landscape, referred to in the Intergovernmental Panel on Climate Change land-use emission accounting procedures as ‘Flooded Lands’ (IPCC, 2006). Where the creation of small bodies leads to new greenhouse gas (GHG) emissions, these can be considered anthropogenic in origin, and should therefore be included in Flooded Lands emissions inventories (Panneer Selvam et al., 2014).

To date, the relatively few regional studies on small, artificial water bodies (hereafter ‘ponds’) have focussed on water and sediment dynamics (Downing et al., 2008;Callow and Smettem, 2009;Verstraeten and Prosser, 2008;Habets et al., 2014). Studies of CH_4 or other GHG emissions from ponds have been limited, and many are restricted to fairly short-term measurements at a small number of sites within a limited geographical area (Downing, 2010;Deemer et al., 2016). The only regional-scale study to date was undertaken in India by Panneer Selvam et al. (2014). In order to quantify the role of artificial ponds in the global CH_4 cycle, as well as their role as a source of anthropogenic emissions, it is necessary both to obtain estimates of CH_4 fluxes from a broader range of sites (and to determine the factors that account for spatial and temporal variability in flux) and also to estimate the surface area contributing to emissions. Surface area estimates can be problematic given the range of water types (small urban lakes to large irrigation ponds) that fall within the definition of ‘ponds’, their frequently high temporal variation in surface area, the sheer number of such water bodies, and their ongoing increase in number over time.

Here, we present the first regional-scale assessment of CH_4 emissions from ponds in the Southern Hemisphere and, following the assessment of Panneer Selvam et al., (2014) only the second regional assessment globally. The assessment was undertaken in the 1.85 million km^2 State of Queensland, Australia. Queensland provides an effective test case for the estimation of CH_4 emissions from ponds because i) it incorporates a high degree of spatial variability in land-use and climate, from desert to humid tropics; and ii) the irregular rainfall patterns and wide spatial coverage of aerial imagery result in a large number of artificial ponds, which are relatively easy to quantify. CH_4 emissions from these ponds can be considered anthropogenic in origin, because past studies of rainforest and agricultural soils in the region have clearly shown these terrestrial landscapes were weak CH_4 sinks prior to inundation (Allen et al., 2009;Scheer et al., 2011;Rowlings et al., 2012).

Our assessment comprised four components, designed to quantify the total anthropogenic CH_4 emission from ponds in Queensland, as well as their variability:

1. Quantify the area of ponds, relative to regional assessments of larger artificial water bodies;
2. Quantify CH_4 emission rates for a wide spectrum of pond types;
3. Determine spatial and temporal variability in their surface area and emission rates;
4. Determine the influence of inundation level on emission rates.

2 Methodology

2.1 Study area description

Queensland, the second largest state in Australia, covers a surface area of 1.85 million km^2 and having a population of 4.75 million people. Land use across the state is dominated by agriculture with over 80% of the total surface area utilised for grazing cattle or irrigated cropping (QLUMP, 2018). The Queensland agriculture sector contributes more than AUD$13 billion per year to the state economy and includes 15 million cattle and sheep as well as 4,526 km^2 of land under irrigation (ABS, 2018). The climate is subtropical or tropical with mean annual temperatures ranging from 27.5 ^{o}C in the state's north to 15.8 ^{o}C in the southern interior. There are large gradients in rainfall across the state ranging from a mean annual rainfall of over 3,000 mm in the coastal north east to less than 100 mm in the arid western regions. Rainfall has a distinct annual pattern with up to 80% falling during the summer months from November to April and is subject to major drought and flood cycles at decadal cycles (Klingaman et al., 2013). The economic importance of agriculture coupled with the need to provide year round water supply for these activities and the lack of predictable rainfall has resulted in the proliferation of artificial water bodies across the whole state (Fig. A1). Under current state law only dam walls in excess of 10 m and 750 ML are referable to the state registry (DEWS, 2017) with 109 dams registered (Referable dams register; http://qldspatial.information.qld.gov.au/catalogue/). The vast majority of artificial water bodies are less than 5 ML (Nathan and Lowe, 2012) and these ponds, therefore, represent an area of major uncertainty in the assessment of land use change assessment and associated greenhouse gas emissions.

2.2 Relative surface area of ponds across the region

The number and relative surface area of ponds in Queensland was derived from the most recent official assessment of land use from March 2018 (QLUMP, 2018). Within the Primary land use classification of "Water" there is a secondary category of artificial "Reservoirs/dam" divided further into "Reservoirs, Water storage and Evaporation basin." The individual water body surface area is provided and all reservoirs and water storages less than 100,000 (10^5) m^2 were extracted from the database. Evaporation basins were excluded, as these are commonly used for salt extraction. These ponds were then compared against two State Government databases from a high resolution assessment of artificial water bodies across the state published in 2014 and 2015. One database contains water bodies greater than 625 m^2 at full supply (Reservoirs – Queensland; http://qldspatial.information.qld.gov.au/catalogue/) and for water bodies less than 625 m^2 a second database was used (Water storage points - Queensland; http://qldspatial.information.qld.gov.au/catalogue/).

Water bodies larger than 625 m^2 contained individual polygons where water body surface area was provided and all water bodies less than 10^5 m^2 were extracted from the database. The database of water bodies smaller than 625 m^2 contained point data providing only the location of waterbodies and no information on their dimensions (A1 b and c). To estimate the surface area of these systems, 100 water bodies were randomly selected using the Subset Features tool in the Geostatistical Analyst toolbox in ArcGIS (Version 10.3, ESRI Inc., Redlands, California, USA). The surface area of selected water bodies was then quantified using high resolution aerial imagery (Nearmap; www.nearmap.com.au). Typical pixel resolution was 7 cm, which greatly improves edge detection of ponds as it can be very challenging to separate the water edge from riparian vegetation stands with coarser-scale data. Pond edges were mapped following the methodology of Albert et al., (2016) where imagery was georeferenced and the water edge was manually traced to create individual polygons for each pond. The mean surface area of all 100 polygons was then used to calculate total surface area of water bodies within this database. All databases were screened to ensure only one water body was reported from each location, with overlapping waterbodies removed. The remaining water bodies were sorted using two different size class classifications: Firstly, we categorised sites into the three smallest size classes (10^2 to 10^3 m^2; 10^3 to 10^4 m^2; and 10^4 to 10^5 m^2) in the Global Reservoir and Dam (GRanD) assessment (Lehner et al., 2011). Secondly, we divided sites into water bodies less than 3,500 m^2 (primarily stock dams) and larger water bodies (primarily irrigation dams and urban lakes), following the findings of Lowe et al., (2005).

2.3 CH_4 emissions from broad spectrum of pond types

To quantify the range of emission rates from ponds, a monitoring program was undertaken across a wide spectrum of ponds including: farm dams (irrigation and stock watering), urban lakes, small weir systems (i.e. small dams leading to widening and slowing of river flows) and rural residential water supplies (Fig. 1). The majority of sites were located in coastal catchments in south east Queensland, Australia as well as one urban lake and three stock dams in Central Queensland (Fig. 2 c).

CH_4 emission rates were measured by deploying between 3 and 16 floating chambers per water body, capturing both peripheral and central zones (Fig. A2). Chamber design followed the recommendations of Bastviken et al., (2015), as these lightweight chambers (diameter 40 cm, 12 L headspace volume and 0.7 kg total weight) were ideally suited to deployment in ponds where both site access and on-water deployments can be challenging. Where possible 24 hour measurements were undertaken, however in three water bodies this was not possible (Table A1) and here measurements lasted between 6 and 8 hours. After each deployment a chamber headspace gas sample was collected following the Exetainer method described in Sturm et al., (2015). CH_4 emission rates were calculated from the change in headspace concentration over time and normalised to areal units (Grinham et al., 2011).

2.4 Spatial and temporal variability in surface area and emission rate

2.4.1 Spatial and seasonal variability across a single water body

Seasonal variability in emission rates were measured at an urban lake (St Lucia 1) where monthly monitoring at a single site was undertaken across an annual cycle. Emissions were monitored following the same methodology as described in the preceding section, and 4 to 5 floating chambers were deployed for each sampling event. Emission rates from this seasonal study were then compared to an intensive spatial survey of the same lake, where 16 chambers were deployed simultaneously across the lake. To better understand spatial patterns in emissions within this pond the water depth and proximity to inflow points were mapped. The bathymetric survey was conducted using a logging GPS depth sounder (Lowrance HDS7 depth sounder, Navico, Tulsa, Oklahoma, USA).

Georeferenced water depth points were imported into ArcGIS interpolated across the whole water body using the inverse distance weighting function.

2.4.2 Variability in water surface area across all monitored ponds

The variability in surface area of each pond monitored in the emissions surveys was analysed using high resolution historical imagery across all monitored water bodies. A time-series of high resolution aerial imagery over a 9 year period from 2009 to 2017 was screened for image quality and appropriate images were selected. The time series data are not consistent across the whole state, the number of discrete images for individual water bodies varied from 3 to 16. Images of individual ponds were georeferenced to a common permanent feature across all images and then the outer water edge was mapped and surface area calculated following Albert et al., (2016). The time series of surface area for individual water bodies was compared to their corresponding surface area at full supply level (A_{FSL}) and expressed as a percentage then grouped into three size classes based on the GRanD classification. This time period also captured the range of rainfall variability across the state with 2010 being the wettest year on record whilst 2013 to 2015 were consecutive drought years (Average rainfall; https://data.qld.gov.au/).

2.5 Effect of inundation status on pond emissions

Given the relatively shallow nature of most ponds, as well as high water use rates, peripheral areas of the water body regularly experience periods of inundation and no inundation as water levels change. The effect of inundation on emission rates was tested on a stock dam (Gatton 4) where measurements were undertaken on peripheral areas during periods of inundation and no inundation. Emission measurements for the inundated period followed the methodology outlined above for the water body emissions survey. Three weeks later water levels within the ponds had dropped and emission measurements were repeated at the same sites which were now exposed. For these emission measurements five chambers (90 mm diameter, 150 mm length) were carefully inserted 50 mm into the ground and care was taken to minimise disturbance to the soil surface. The headspace of each chamber was flushed with ambient air to remove headspace contamination due to chamber insertion, then the sampling port of each chamber was sealed. After the deployment period, a gas headspace sample was collected and CH_4 concentration analysed.

2.6 Statistical analyses and regional scaling of emissions

Emissions rates and surface area data were analysed using a series of one-way analyses of variance (ANOVAs) with the software program, Statistica V13 (Dell Inc., 2016). Analysis of emissions rates collected during the monthly monitoring study and the inundation study used sampling month or inundation status as the categorical predictors and chamber emission rates as the continuous variable. Emission rates from individual water bodies collected during the broad survey were first pooled into four primary use categories (irrigation, stock, urban and weirs) or three different GRanD size classes and these categories were used as the categorical predictors. The primary use of each pond was provided by pond owners or managers, in the case of urban lakes that had both aesthetic and stormwater functions these were classified as urban (Table A1). 22 ponds were included in this survey with four irrigation ponds, nine stock watering ponds, seven urban ponds and two weirs. Changes in water surface area (as a percentage of A_{FSL}) from individual water bodies were pooled into three GRanD size classes and these categories used as the categorical predictors. Where necessary, continuous variable data were log transformed to ensure normality of distribution and homogeneity of variance (Levene's test) with post hoc tests performed using Fisher's LSD (least significant difference) test (Zar, 1984). Tests for normality were conducted using Shapiro-Wilks tests as recommended by Ruxton et al., (2015). The non-parametric Kruskal–Wallis (KW) test was used for continuous data which failed to satisfy the assumptions of normality and homogeneity of variance even after transformation. Statistical results were reported as follows: Test applied (Fisher's LSD or Kruskal-Wallis test), the test statistic (F or H) value and associated degrees of freedom with p-value.

Emissions were scaled to water body size classes following two different approaches. Firstly, emissions were grouped according to their respective GRanD size class. These match the size class of water bodies used in the emissions monitoring of this study, and the GRanD database was used in the most recent global synthesis of greenhouse gas emissions from reservoirs (Deemer et al., 2016). Secondly, water bodies less than 3,500 m^2 in area were assumed to be primarily stock dams and larger water bodies primarily irrigation dams (Lowe et al., 2005). To extrapolate pond emission rates to regional scales, an appropriate measure of centrality should be used. Three common measures, arithmetic mean, geometric mean and median values, were calculated for each water body category and size class. To assess the most suitable measure of centrality for water body emissions, normal probability plots of raw and log transformed emissions data were generated and tested using the Shapiro-Wilks test. The emissions data from all replicate measurements clearly followed a log normal distribution (Fig. A3) and, therefore, the geometric mean would provide the most appropriate measure of centrality for this data (Ott, 1994;Limpert et al., 2001). Fluxes were scaled to annual rates using the cumulative surface area of water bodies and the respective emissions rate for each size class using the geometric means. The variability in geometric mean was given by the exponential of the 95% confidence interval range of log transformed data. Emissions for water bodies less than 3,500 m^2 were scaled using stock dam rates and larger water bodies (3,500 m^2 to 10^5 m^2) using rates obtained from irrigation dams and urban lakes. Total fluxes from respective size classes were then combined to provide regional estimates. Annual fluxes of CH_4 were converted to CO_2 equivalents assuming a one hundred year global warming potential of 34 (IPCC, 2013).

3 Results

3.1 Relative surface area of ponds

The state wide land use assessment identified 13,046 ponds across Queensland, occupying a total surface area of approximately 467 km^2 (Fig. 2 c). However, with the inclusion of the additional datasets the number of ponds increased over 20 times to a total of 293,346, and the surface area more than doubled to 1,087 km^2. Ponds were widely distributed across the state, but over 78% of ponds were located on grazing land, suggesting that stock dams represent the primary water body type (Fig. 2 a). The majority of ponds were confined to regions of the state were rainfall isohyets were above 600 mm (Fig. 2 b) and heavily concentrated in cropping and residential areas in the central and south eastern parts of the state (Fig. 2 c). These findings highlight the importance of striving to incorporate all artificial water bodies into flooded land emission assessments; omitting water bodies below a size threshold can lead to a dramatic under-estimation of the total number of water bodies present, and a considerable underestimate of the available surface area for CH_4 emissions.

3.2 CH_4 emissions from ponds

All 22 water bodies monitored in this study were shown to be emitters of CH_4, and emission rates ranged from a minimum of 1 mg m^{-2} d^{-1} to a maximum of 5,425 mg m^{-2} d^{-1} (Table A1). Only one water body (Mt Larcom 3) had a maximum rate below the reported upper range (50 mg m^{-2} d^{-1}) for diffusive fluxes found in larger water bodies in this region (Grinham et al., 2011;Musenze et al., 2016). Mean flux rates of only four individual water bodies were below 50 mg m^{-2} d^{-1} (Table A1) suggesting ebullition to be the dominant emission pathway in these systems. Grouping ponds according to their primary use resulted in no significant differences in emissions rates between irrigation dams, stock dams and urban lakes, however, weirs were significantly higher ($F_{(3,121)} = 6.43$, $p < 0.001$) than all other categories (Fig. 3 a). Mean emission rates were however higher in stock water bodies (168 mg m^{-2} d^{-1}) compared with irrigation and urban bodies (84 and 129 mg m^{-2} d^{-1}, respectively). Weir water bodies had mean emission rates of 730 mg m^{-2} d^{-1}, more than four times higher those of any other category (Fig. 3 a). Grouping ponds according to their GRanD size classes resulted in significantly higher emissions rates ($KW\text{-}H_{(2,121)} = 7.354$, $p < 0.05$) from ponds in 10^2 to 10^3 m^2 size class compared to 10^4 to 10^5 m^2 (Fig. 3 b). Overall, mean emissions decreased with increasing size class. Note that all weir sites fell into the smallest size category.

3.3 Spatial and temporal variability in surface area and emission rate

3.3.1 Spatial and temporal variability within a single pond

Observed emissions rates from the high-resolution spatial study, carried out in December 2017, ranged over two orders of magnitude from under 40 mg m^{-2} d^{-1} to over 3,500 mg m^{-2} d^{-1} (Fig. 4). Emissions were highest in the shallow southwest sector of the pond, adjacent a large stormwater inflow point, as well as along the western boundary where numerous overhanging riparian trees are located along with a second stormwater inflow point (Fig. 4).

Monthly emissions were moderately variable across the annual cycle and mean rates ranged from 176 to 332 mg m^{-2} d^{-1}. No significant difference in emissions rates ($KW\text{-}H_{(11,50)} = 3.56$, $p = 0.98$) were observed between sampling events (Fig. 5). Mean rates observed during the monthly monitoring were similar to chamber rates from the intensive spatial study (274 mg m^{-2} d^{-1}).

3.3.2 Variability in water surface area across all monitored ponds

Variability in water surface area is strongly related to water body size class (Fig. 6). Mean surface area within the smallest size class was only 64% of A_{FSL}, this increased to 84% in the intermediate size class and was to 94% in the largest size class (Fig. 6). Smaller ponds had a significantly lower surface area relative to A_{FSL} ($KW\text{-}H_{(2,231)} = 50.523$, $p < 0.001$) compared to larger size classes and were more variable (Fig. 6). Regional emissions estimates therefore need to correct for the differences in water body surface area relative to predicted A_{FSL}, particularly, in the smaller size classes.

3.4 Effect of inundation on pond emissions

The water surface area of a single stock dam ranged from 395 to 2,808 m^2 over a 40 month period (Fig. 7 a) with an outer band of 580 m^2 undergoing frequent inundation cycles (May 2016 to Dec 2017 - Fig. 7 a). Emissions rates from peripheral areas during an inundated period were significantly higher (more than one order of magnitude) compared with emissions when not inundated ($KW\text{-}H_{(1,10)} = 6.818$, $p < 0.001$; Fig. 7 b). This modifier of rates will primarily impact emissions from smaller size classes which have greater variability in water surface area (Fig. 6). An additional implication is in the importance of designing monitoring studies where emissions rates are quantified from both peripheral and central areas for each system. Rates monitored only in peripheral areas will likely bias towards lower emissions, particularly if these have undergone recent inundation.

4 Discussion

4.1 Relative importance of pond emissions to regional flooded land inventories

The findings of this study clearly demonstrate ponds are an underreported and important CH_4 emission source in Queensland, and likely also globally. The official land use assessment of Queensland underestimates the surface area of ponds by 57%, and the total number of water bodies by more than an order of magnitude. These findings highlight the importance of striving to incorporate all artificial water bodies into flooded land emission assessments; omitting water bodies below a size threshold can lead to a substantial under-estimation of the total number of water bodies present, and a considerable underestimate of the available surface area for CH_4 emissions. The revised total surface area of artificial water bodies across Queensland increased by 24% to just over 3,248 km^2 (Table A2). Mean annual CH_4 fluxes from ponds for the State of Queensland ranged between 1.7 and 1.9 million t CO_2 eq (Table 1) depending on the scaling approach. The uncertainty in mean emissions ranged from a lower limit of 1.1 million t CO_2 eq to an upper limit of 3.2 million t CO_2 eq. Remarkably, mean total emissions from ponds represent approximately 10% of Queensland's land use, land use change and forestry sector (NGERS, 2015) emissions using either scaling approach.

Future regional and global emissions estimates would be greatly improved with the inclusion of ponds, as their proliferation has been noted in five continents. In the continental United States ponds have been shown to cover 20% of total artificial water body surface area (Smith et al., 2002); in South Africa there are an estimated 500,000 ponds (Mantel et al., 2010); in Czechoslovakia ponds make up over 30% of total artificial water bodies surface area (Vacek, 1983); and in India ponds are estimated to comprise 6,238 km^2, or over 25% of India's artificial water body surface area (Panneer Selvam et al., 2014).

4.2 Pond emission pathways

Emissions rates from ponds observed in this study are consistent with ebullition being the dominant pathway. Diffusive emissions from studies of three larger water bodies in the region found the upper limit for diffusive emission was 50 mg m^{-2} d^{-1} (Grinham et al., 2011;Musenze et al., 2016) and only five ponds had emission rates below this level. Ebullition was observed at all ponds with maximum rates all in excess of 50 mg m^{-2} d^{-1} with the exception of only one stock dam (Mt Larcom 3) where the maximum rate was 19 mg m^{-2} d^{-1}. This is a consistent finding with larger water bodies in the region where ebullition has been shown to dominate total emissions (Grinham et al., 2011;Sturm et al., 2016). The relatively higher emissions from smaller pond size classes is consistent with previous observations of increased ebullition activity in shallow zones, particularly water depths less than 5 m (Keller and Stallard, 1994;Joyce and Jewell, 2003;Sturm et al., 2016). Virtually all ponds within the smaller size classes would be less than 5 m deep. In addition, ponds trap large quantities of sediment and organic material (Neil and Mazari, 1993;Verstraeten and Prosser, 2008) and these deposition zones have been identified as methane ebullition hotspots in larger water bodies (Sobek et al., 2012;Maeck et al., 2013). The pattern in emissions from the intensive spatial study in an urban lake, where shallow areas adjacent stormwater inflows were shown to be ebullition hotspots, have also been observed in larger water bodies were ebullition activity was highest adjacent to catchment inflows (DelSontro et al., 2011;Grinham et al., 2017;de Mello et al., 2017). The emissions from small weirs were clearly dominated by ebullition, which is consistent with emissions from three larger weirs where rates ranged from 1,000 to over 6,000 mg m^{-2} d^{-1} (Bednařík et al., 2017). Weirs intercept the primary streamflow pathways and will likely cause large quantities of catchment derived organic matter to deposit within the weir body which, coupled to the shallow nature, results in high rates of ebullition. Overall, the rates observed for all categories, except irrigation dams, were in the upper range of reservoir areal flux rates reported in global reviews (St. Louis et al., 2000;Bastviken et al., 2011;Deemer et al., 2016), reflecting the dominance of the ebullition pathway in ponds.

4.3 Challenges in scaling emissions

Efforts to develop flooded land emission inventories rely heavily on the emission rate used to scale the surface area of water bodies' within selected categories. Given the high variability in emission rates within and between individual ponds and relatively low replication, it is critical to select an appropriate measure of centrality (arithmetic mean, geometric mean or median) in order to scale regionally and globally (Downing, 2010). For rice paddies, septic tanks, peatlands and natural waters (Aselmann and Crutzen, 1989;Dise et al., 1993;Diaz-Valbuena et al., 2011;Bridgham et al., 2006) the geometric mean has been applied. Likewise, in this study the log normal distribution of emissions data indicated the geometric mean as the most appropriate measure and the total emission rates using this measure fell within the reported range from larger artificial water bodies in the region (Grinham et al., 2011;Sturm et al., 2016). However, the geometric mean for all water body categories and size classes were less than half of their respective arithmetic mean values (Fig. A4). For irrigation, stock and urban water bodies, geometric mean values were actually outside of 95% confidence interval limit for the arithmetic mean (Fig. A4 a and b). Geometric mean and median values were similar across all water body categories and size classes and these measures, therefore, represent conservative emissions rates from ponds. This raises an important issue with scaling ebullition dominated water bodies as there is always going to be a high likelihood of detecting a small number of very high rates which will invariably give rise to log normal data distributions. Future studies will focus on determining whether the conservative estimates generated through the use of geometric means approximate the true emissions from ponds.

5 Future research

Continued efforts to quantify regional pond abundance, particularly smaller size classes, should be a research priority as this will greatly improve flooded land surface area estimates available for emissions. The increased coverage, availability and resolution of satellite imagery as well as more sophisticated methods to identify water bodies (Verpoorter et al., 2014) will support these efforts. However, it is critical to continually update regional assessments as the annual increase in farm ponds has been estimated to be as high as 60% in some parts of the globe (Downing and Duarte, 2009). Regional assessments should also correct for differences in pond surface area, particularly in the smaller size classes, as this study has demonstrated actual surface area can be significantly smaller than the surface area at full supply level, A_{FSL}.

Increasing both the number and type of pond within each size class should be a research priority for emissions monitoring studies. This will allow increased confidence in the selection of an appropriate measure of centrality as well as reducing uncertainty in the expected range of emission rates within each pond category. When designing a monitoring study it is important to ensure emissions rates are quantified from both peripheral and central areas for each pond. This study demonstrated that measurements taken only in peripheral areas will likely bias towards lower emissions particularly in ponds that experience rapid changes in water level and, therefore, inundation status of peripheral areas. The high variability in emission rates within ponds noted from this study, highlights the importance of ensuring chambers cover the widest possible spatial scale during a measurement campaign. This will increase the likelihood of detecting ebullition zones which are likely the dominant emission pathway. Research into both pond surface area and CH_4 emission rates will allow greater understanding of their importance to flooded land emission inventories at both regional and global scales.

Data Availability

The data that support the findings of this study are available from the corresponding author upon request.

Author contribution

AG conceived, designed and conducted the study and co-wrote the manuscript; CE, CL, DB and BS conceived, designed the study and contributed to the manuscript; SA, ND and MD conducted the study and contributed to the manuscript.

Competing interests

The authors declare no competing financial interests.

Acknowledgements

We gratefully acknowledge the following for providing access to ponds: R and L Prange; J and M Gale; M Bauer; S Green; T Connolly. In addition, we are grateful for the background information regarding the primary use of the ponds. We gratefully acknowledge M Fluggen for laboratory and logistical support.

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Discussion started: 2 July 2018

Tables

Table 1. Summary of Queensland small water bodies classified using two different relative size classifications. The number of water bodies, corrected surface area of size class and total mean annual emissions. Approach 1: emissions for water bodies less than 3,500 m^2 were assumed to be stock dams and larger water bodies irrigation dams (Fig. 3 a), Approach 2: emissions for GRanD size classes were taken from Figure 3 b.

Approach 1					
Water body size (m^2)	**Number**	**Surface area (km^2)**	**Total emissions (t CO_2 eq yr^{-1})**		
			Mean	*Lower limit*	*Upper limit*
< 3,500	227,397	243	507,633	278,205	926,267
3,500 to 10^5	65,949	844	1,158,069	782,244	1,714,458
Total	**293,346**	**1,087**	**1,665,702**	**1,060,448**	**2,640,725**
Approach 2					
Water body size (m^2)	**Number**	**Surface area (km^2)**	**Total emissions (t CO_2 eq yr^{-1})**		
			Mean	*Lower limit*	*Upper limit*
10^2 to 10^3	108,526	50	241,262	112,316	518,243
10^3 to 10^4	163,803	400	868,201	513,740	1,467,225
10^4 to 10^5	21,017	637	759,247	462,561	1,246,228
Total			**1,868,710**	**1,088,617**	**3,231,695**

Figures

Figure 1. Oblique drone images showing examples of ponds where CH_4 emissions were monitored during this study: a) urban lake (St Lucia 1); b) stock dams in foreground (including Gatton 4), irrigation dam in background; c) small weir showing high organic loading upstream of wall (Mt Cootha); d) rural residential dam (Greenbank).

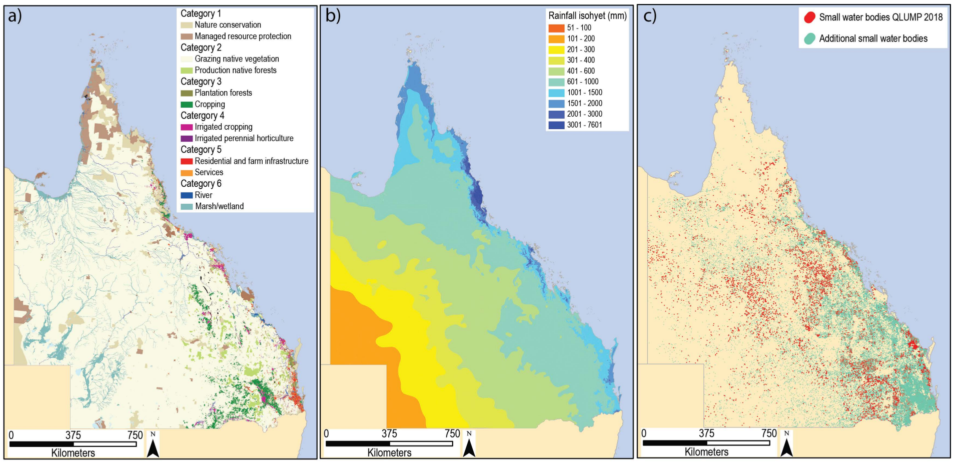

Figure 2. a) 2018 state wide assessment showing the relative surface area occupied by secondary land use categories (QLUMP, 2018). Note the legend shows the two largest land uses within each category: Category 1 is Conservation and Natural Environments; Category 2 is Production from Relatively Natural Environments; Category 3 is Production from Dryland Agriculture and Plantations; Category 3 is Production from Dryland Agriculture and Plantations; Category 4 is Production from Irrigated Agriculture and Plantations; Category 5 is Intensive Uses; Category 6 is Water. b) Mean annual rainfall isohyets across Queensland from 30 period of 1961 to 1990 (http://www.bom.gov.au accessed March 2018). c) Location of ponds identified from the land use assessment (QLUMP 2018) and two additional state wide assessments (see text).

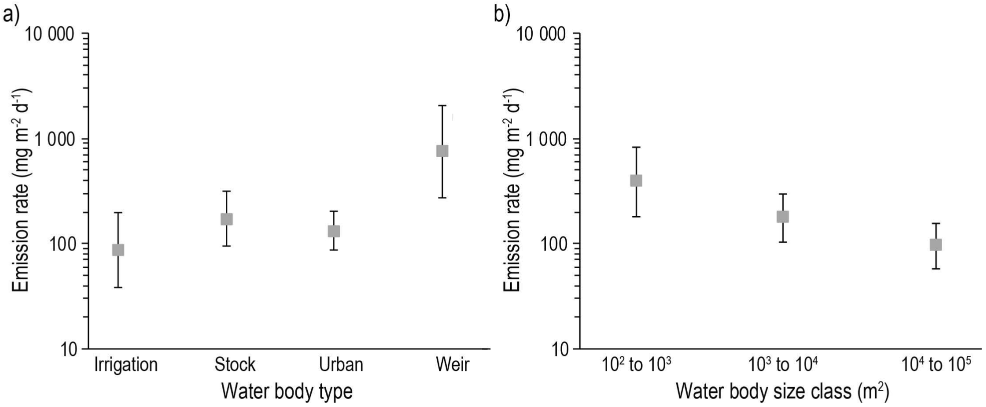

Figure 3. Mean CH_4 emissions across a) four categories of small water bodies (irrigation dams, stock dams, urban lakes and weirs) and b) three GRanD water body size classes. Values indicate geometric mean emission rates and 95% confidence intervals (± 95% CI).

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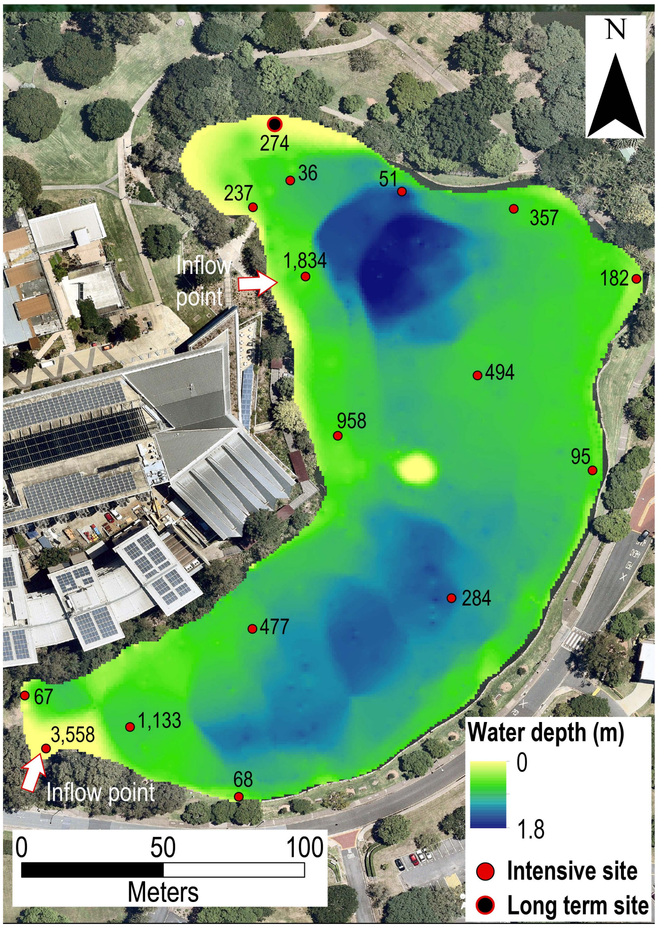

Figure 4. Sampling site location and chamber emission rates (mg m^{-2} d^{-1}) across an urban lake (St Lucia 1) relative to water depth and proximity to stormwater inflow points.

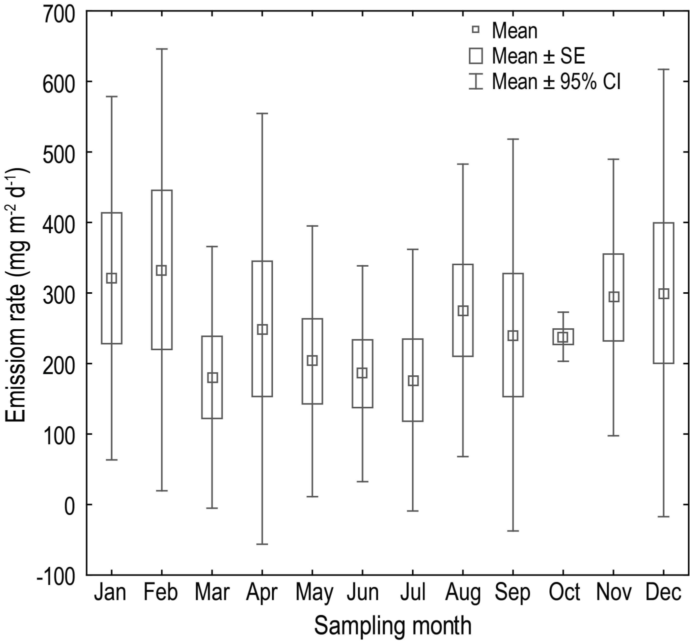

Figure 5. Monthly CH_4 emissions from a single monitoring site on an urban lake (St Lucia 1) across the annual cycle. Values indicate mean emission rates ± SE (standard error) and 95% CI (confidence intervals).

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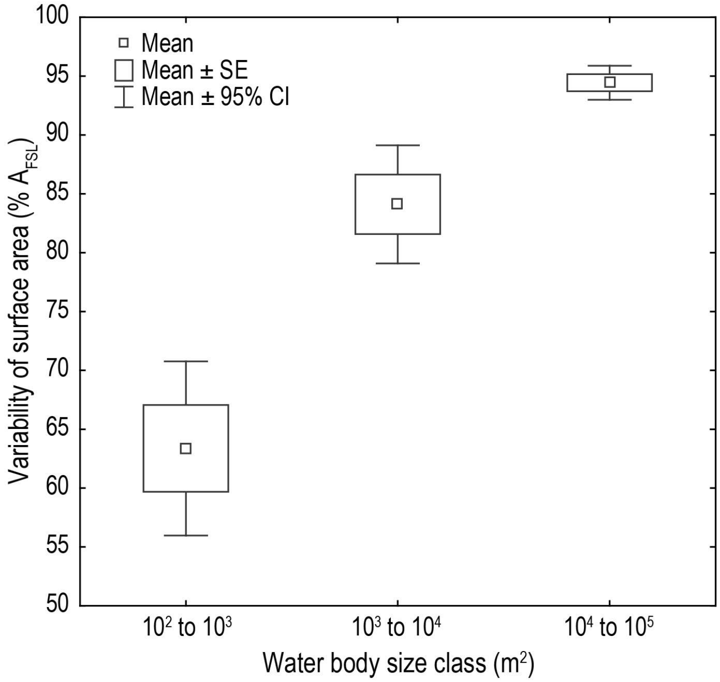

Figure 6. Variability in water surface area as a percentage of A_{FSL} between three GRanD database size classes of ponds. Values indicate mean surface area ± SE (standard error) and 95% CI (confidence intervals).

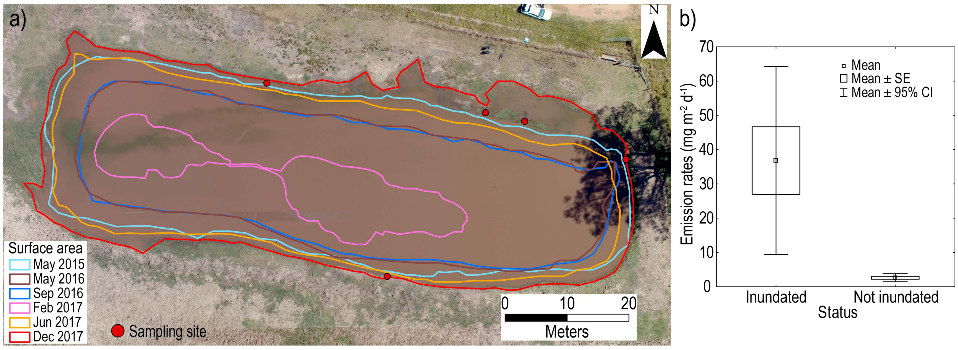

Figure 7. a) Changes in surface area of stock dam (Gatton 4) over a 40 month period. b) Emissions rates from peripheral zones during a period of inundation and no inundation. Values indicate mean emission rate ± SE (standard error) and 95% CI (confidence intervals).

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Manuscript under review for journal Hydrol. Earth Syst. Sci.
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Appendix

Table A1: Selected characteristics from individual ponds showing: primary use of each system; surrounding land-use type; location of system latitude (Lat) and longitude (Long); average surface area (SA) in m^2; mean, median, minimum (Min) and maximum (Max) methane emission rates (mg m^{-2} d^{-1}); number of chamber measurements on individual systems (Cham). Primary uses included the following: irrigation for cropping; stock watering for cattle and horses; urban uses included stormwater management and aesthetic purposes; weirs for water supply and stream flow monitoring. * indicates water bodies where repeat sampling was conducted; # indicates water bodies where deployments of less than 24 hours were conducted.

Area	Primary use	Land-Use	Lat	Long	SA	Arth Mean	Geo Mean	Median	Min	Max	Cham
Gatton 1*	Irrigation	Grazing	-27.5541	152.3412	25,903	785	590	527	238	1,648	6
Gatton 2*	Irrigation	Grazing	-27.5548	152.3394	3,450	581	170	140	17	2,261	6
Gatton 3*	Stock	Grazing	-27.5615	152.3434	1,041	1,149	905	980	314	2,007	12
Gatton 4*	Stock	Grazing	-27.5625	152.3447	1,893	63	55	63	20	109	6
Gatton 5	Irrigation	Cropland	-27.5537	152.3503	30,458	129	122	110	89	186	3
Gatton 6	Stock	Cropland	-27.5546	152.3488	446	1,229	724	844	93	3,635	6
Port precinct#	Urban	Settlement	-27.3917	153.1676	38,285	144	57	68	8	357	3
St Lucia 1*	Urban	Settlement	-27.4996	153.0163	22,727	632	282	279	36	3,558	16
St Lucia 2	Urban	Settlement	-27.4984	153.0173	4,291	92	83	76	51	148	3
St Lucia 3	Urban	Settlement	-27.4981	153.0167	1,755	56	49	43	27	115	5
Pinjarra 1*	Irrigation	Grazing	-27.5372	152.9139	56,782	34	15	20	2	122	10
Pinjarra 2	Stock	Grazing	-27.5294	152.9242	1,943	205	59	277	2	335	3
Pinjarra 3	Stock	Grazing	-27.5294	152.9227	210	193	143	107	67	404	3
Oxenford	Urban	Settlement	-27.8924	153.2997	36,938	97	94	81	76	133	6
Mt Larcom 1	Stock	Grazing	-23.8008	150.9558	5,025	574	37	18	1	2,051	5
Mt Larcom 2	Stock	Grazing	-23.806	150.9574	1,256	48	45	49	26	70	3
Mt Larcom 3	Stock	Grazing	-23.8015	150.9446	16,093	17	17	18	14	19	3
Fig Tree Park	Urban	Settlement	-27.5394	152.9682	8,357	709	301	289	19	1,850	5
Greenbank#	Stock	Settlement	-27.7249	152.9779	575	290	166	188	29	755	4
Lake Alford#	Urban	Settlement	-26.2152	152.6848	21,689	49	29	62	5	79	3
Mt Cootha*	Weir	Forest	-27.4763	152.9642	580	2,493	1,405	2,337	368	5,425	6
Indooroopilly	Weir	Settlement	-27.5027	152.988	436	413	274	314	77	947	4

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Manuscript under review for journal Hydrol. Earth Syst. Sci.
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Table A2: Surface area (SA) of Queensland artificial water bodies within each GRanD database size class showing the official land use assessment estimates (QLUMP, 2018) and the revised estimates for the smallest three size classes found in this study.

GRanD size class (m^2)	QLUMP SA (km^2)	Revised SA (km^2)
10^2 to 10^3	0.005	50.3
10^3 to 10^4	8.4	400
10^4 to 10^5	459	637
10^5 to 10^6	605	605
10^6 to 10^7	555	555
10^7 to 10^8	553	553
10^8 to 10^9	448	448
Total	**2,629**	**3,248**

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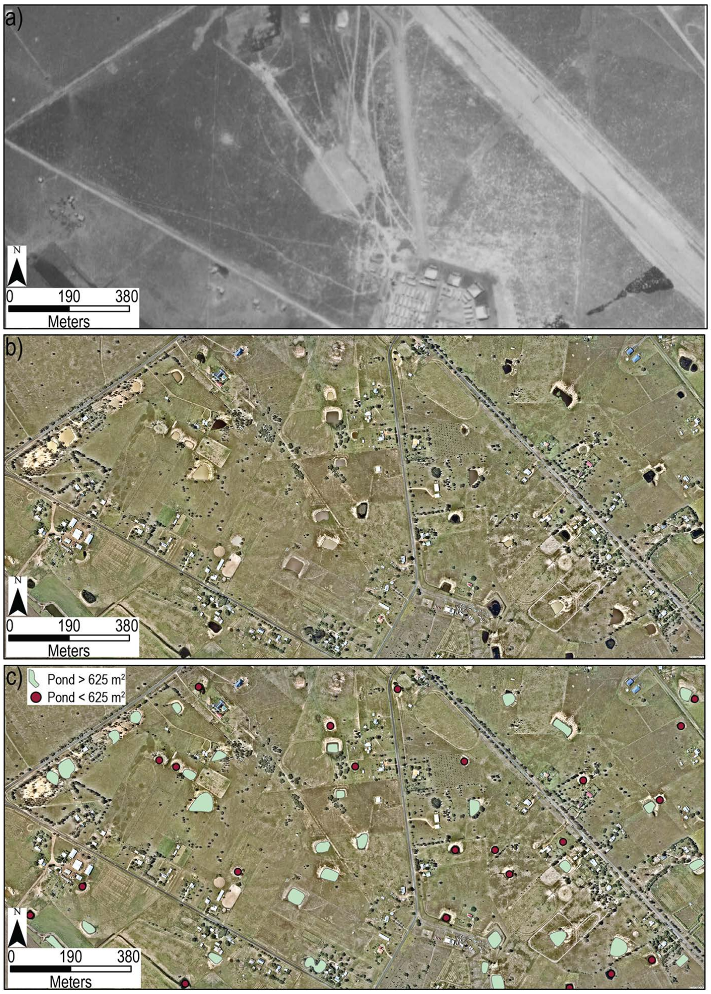

Figure A1. Historical changes in pond distribution from a 2.7 km^2 area in South East Queensland, Mt Tarampa (27°27'44"S, 152°28'59"E). a) 1944 aerial images showing 2 ponds, b) 2017 aerial image showing 54 ponds and c) showing the relative distribution of ponds from > 625 m^2 database and < 625 m^2 database, together result in a density of 20 ponds km^{-2}.

Figure A2. An oblique drone image showing a nine floating chamber deployment setup targeting peripheral and central zones on a stock watering dam (Gatton 3).

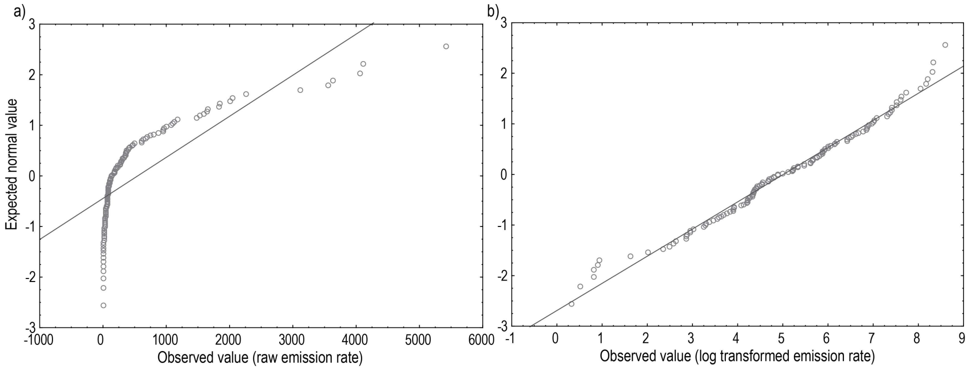

Figure A3. Normal probability plots for a) raw methane emissions and b) log transformed emissions data. Shapiro-Wilks tests p-value for raw emissions data was < 0.001 and failed the normality test; p-value for log transformed emissions data was 0.081 indicating data was normally distributed.

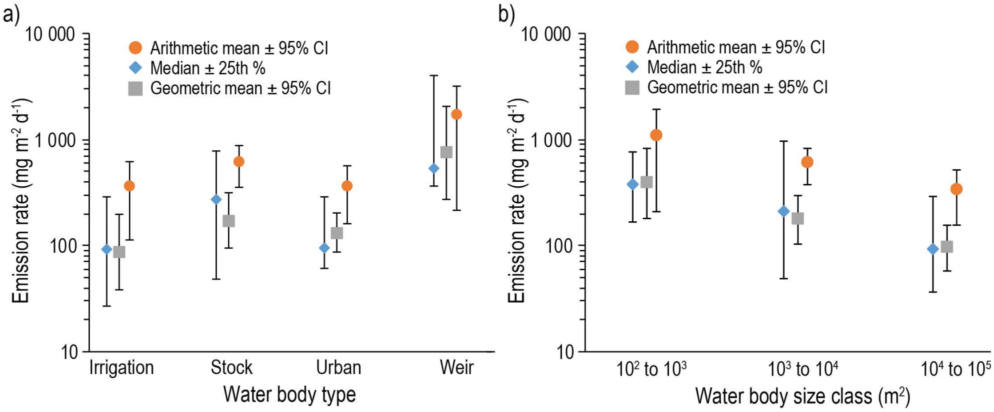

Figure A4. Three measures of centrality for methane emissions across a) four categories of small water bodies (irrigation dams, stock dams, urban lakes and weirs) and b) three GRanD water body size classes. Error for each measure are as follows: median emission rates and interquartile range (± 25th %), arithmetic 5 and geometric mean emission rates and 95% confidence intervals (± 95% CI).