Estimation of Nutrient Fluxes from Suburban Watersheds in Japan using the SWAT Model: Current Issues and Future Directions

Yuta Shimizu[1,2], Shin-ichi Onodera[3] and Kenji Matsumori[2]

[1] *JSPS Research Fellow*

[2] *Western Region Agricultural Research Centre, National Agriculture and Food Research Organization, 6-12-1 Nishifukatsu-cho, Fukuyama, Japan*

[3] *Graduate School of Integrated Arts and Sciences, Hiroshima University, 1-7-1 Kagamiyama, Higashi-Hiroshima, Japan*

Abstract

This article presents a critical review of the role of domestic wastewater, land use change, and climate change in the estimation of nutrient fluxes in suburban watersheds using the SWAT model. Domestic wastewater has the greatest potential effect on nutrient flux but may have been ignored in previous studies because it is difficult to assess compared with the contributions from sewage treatment plant effluent. Considerable uncertainty applies to the estimation of domestic wastewater quantity and quality. The effect of land use changes on nutrient flux should be considered in the suburban zone because such changes are mostly rapid and unidirectional, from rice paddy field to other land use including urbanization process. Hence, the dynamical land use changing function is needed for SWAT estimation in suburban watersheds. The flow regime shift that is induced by climate change may be a key driver for changes in nutrient flux on SWAT estimation in suburban watersheds because increase of events of flood and drought affect to material transportation. Both of changes in land use and climate could be eventually related to domestic wastewater in terms of urbanizing land use change and overflow of combined sewer by heavy rainfall. Improved estimation methods for domestic wastewater are necessary for the better estimation of nutrient flux in future development of the SWAT.

Keywords: climate change, domestic waste water, land use change, nutrient flux, suburban watershed, SWAT

1. Introduction

Modelling water and nutrient dynamics at the watershed scale is an indispensable approach to solving water resource issues and maintaining the water environment into the future. Monitoring of river water quality in Japan has occurred since the 1970s, when rapid industrialization had heavily polluted the water environment. Monitoring is conducted monthly when the river flow rate is low because the focus of measurements is the controlled regular releases of industrial and domestic wastewater. The volume of material transported from the watershed is therefore likely underestimated because the water quality monitoring record has poor temporal resolution and excludes data from high river flows, despite river runoff being measured every 10 minutes. High flows are especially important when sediment and bound phosphorus are important contributors to nutrient flux (House and Denison, 2002; Withers and Jarvie, 2008). A modelling approach with a non-point source pollution model such as the Soil and Water Assessment Tool (SWAT) can be an effective way of filling the data gaps left by low-resolution monitoring. SWAT is a conceptual, continuous, time series model that was developed in the early 1990s as a tool to assist water-resource managers in assessing the impact of land-management and climate on the water supply and nonpoint-source pollution in watersheds and large river basins (Arnold and Fohrer, 2005). SWAT is recognized as one of the major watershed models in recent years (Wellen et al., 2015).

Before the application of SWAT to a target watershed, the characteristics of the watershed must be well understood, because most target rivers will be substantially affected by human activities. Typically, watersheds can be divided into three zones (urban, suburban, and rural) according to the intensity of human activities as indicated by population density and land use mix (Fig. 1) The residential dominated urban zone has the highest potential nutrient flux from domestic wastewater, is defined as sewage derived principally from dwellings or business buildings, associated with having the highest population density of the three zones. However, nutrient removal at sewage treatment plants reduces the actual nutrient flux considerably. The suburban zone, a mixture of residential and agricultural land uses, is influenced by the combined fluxes of domestic wastewater and agricultural wastewater . The population density is less than in urban areas, suggesting that the total amount of domestic wastewater should be less than from urban areas. However, lower rates of wastewater treatment mean that suburban areas actually have higher fluxes of domestic wastewater and nutrients than urban areas.

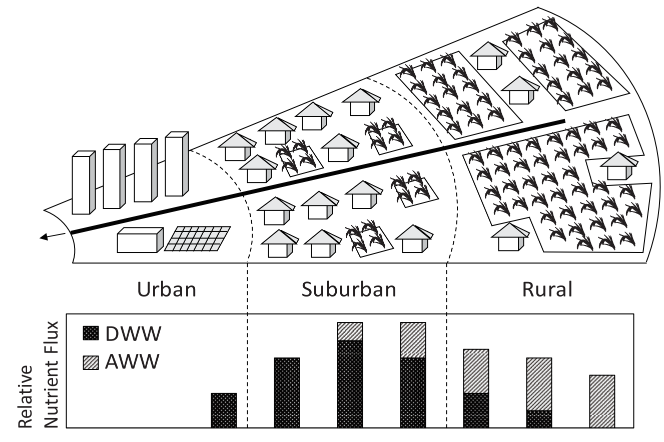

Fig. 1 Schematic diagram of watershed zones based on population and potential pollution load stemming from human activities. DWW: domestic wastewater, AWW: agricultural wastewater

New satellite residential developments (sometimes called "bed towns"), from which workers commute to a central urban area, arose in Japan during the period of rapid economic growth. Such towns in the suburban zone were equipped only with simple septic tanks for domestic wastewater treatments. Although simple septic tanks remove organic matter, they are not able to remove nutrients. Therefore, the nutrient flux is more closely aligned with the actual population. Although such bed towns have been progressively provided with mains sewerage and higher levels of sewage treatment (nutrient removal), domestic wastewater is still considered a major source of nutrient flux from suburban areas. Agricultural wastewater is considered a secondary source of nutrients in suburban areas because of remnant agricultural land among the sprawling bed towns.

The rural zone is mainly dominated by agricultural land uses such as rice paddies, vegetable fields, fruit orchards, livestock production, and woodlots. The population is much lower than in the other zones and the major source of nutrient flux is agricultural wastewater.

From the characteristics of the three zones, it could be considered that suburban areas have the most polluted parts of watersheds and are the most deserving of having numerical models applied for improving the water environment through testing different scenarios of best management practices. In addition, the changing pattern of river flow due to both land use change and climate change should be considered because of the potential influence they have on transportation capacity.

The objective of this article is to present a critical review of modeling domestic wastewater, land use change, and climate change in SWAT because of their importance as factors that affect nutrient flux in suburban watersheds.

2. Domestic Wastewater

It is unusual for a mains sewer system to service the entire watershed in suburban and rural zones in Japan. Community-scale sewerage systems are provided to limited areas of suburban and rural zones, but septic tanks are still a major form of domestic wastewater treatment in the zones in Japan (Ministry of the Environment, 2014) as well as the world wide (Withers et al., 2014; Richards et al., 2016). The average removal ratios of conventional septic tanks designed for less than 10 people are 28% for total nitrogen (TN) and 16% for total phosphorus (TP) (Fujimura, 2006). The average concentrations in domestic wastewater effluent after treatment by conventional septic tank are 26 mg L^{-1} for TN and 3.2 mg L^{-1} for TP (Fujimura, 2006). Although the nutrient flux from a single septic tank is tiny, at the watershed scale the cumulative effect is large because septic tanks are mainly installed in the rural and suburban zone (Haruta and Sakurai, 2010; Withers et al., 2011).

Identifying the true value of model parameters for nutrient transport is extremely difficult. Although a large number of articles about SWAT applications to suburban or rural watersheds for estimation of nutrient flux are found, researchers often achieve reproducibility of model estimation by finding mathematical solutions that optimize parameter values with no consideration of domestic wastewater input. It might be considered that domestic wastewater input is ignored due to its small contribution or is completely unrecognized of its existence and importance. However, there is a risk of over- or underestimation on the nutrient flux and its sources, if model is applied to the watershed that is influenced by domestic wastewater. For instance, Guse et al. (2007) compared GROWA/MEPhos and SWAT for the reproducibility of estimates of phosphorus flux. Both models produced similar mean annual phosphorus flux; however, SWAT estimated a phosphorus flux from soil erosion six times larger than that of GROWA/MEPhos. GROWA/MEPhos estimated that 65% of the total amount of phosphorus was from point sources related to the sewerage system in urban areas, including combined sewer overflows, whereas SWAT estimated that 60% of the total was coming from agricultural areas through soil erosion. SWAT failed to account adequately for domestic wastewater, and the researchers achieved a reasonable annual mean flux by forcing the soil phosphorus flux-related parameters to unrealistic values. Because there are a limited number of adjustable parameters, this could cause a flow-on error in the estimation of phosphorus concentration in groundwater flow to rivers, forcing it to unrealistically high concentrations to compensate for the deficiency in phosphorus sources (Jackson-Blake et al., 2015).

Figure 2 shows the dissolved inorganic phosphorus (DIP) concentration in the streamwater of a suburban watershed estimated by SWAT. The model underestimated DIP concentration by up to 50% when domestic wastewater inputs were ignored (Fig. 2, “without domestic wastewater”) and parameters related to phosphorus were assigned realistic values based on field survey (Fujimura, 2006). However, the estimates are closer to observed if domestic wastewater or sewage effluent data are included (Fig.2, “with domestic wastewater”). If the target watershed is subject to intensive human activities, including generation and management of domestic wastewater, it is rare for the Nash–Sutcliffe efficiency index and coefficient of determination (r^2) to exceed 0.2 if the model does not consider sewage effluent (Jackson-Blake et al., 2015).

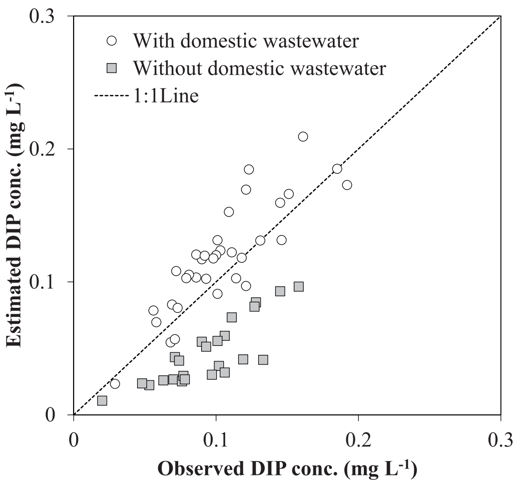

Fig. 2 Dissolved inorganic phosphorus (DIP) concentration in a suburban watershed estimated using SWAT with and without estimated inputs of domestic wastewater. Modified from Shimizu et al. (2013)

Although SWAT has the advantage of estimating nutrient fluxes from non-point sources, especially from agriculture, it is not designed for, and therefore not good at estimating, point sources. However, we consider SWAT is one of the best models available for estimation of nutrient flux because it can produce good results if reasonable parameters for domestic wastewater are determined separately and added to SWAT as point sources. Moreover, the effects of intensive livestock farming, especially piggeries, should be considered because they can be statistically significant sources of effluent in the overall model estimation. However, for all effluent point sources it is difficult to know the amount and timing of discharges in the model routine. For estimating domestic wastewater, the statistical data about coverage ratio of sewage available area and its wastewater treatment types in the all of the cities in Japan is well documented by the government. In addition, the data about location of major sewage treatment plants in Japan is provided through the internet as GIS format. However, in the most of cases, the spatial distribution of sewered area is not available as GIS format even if the population of every small districts in the entire cities of Japan is provided as the format. Some of CAD based sewage connection schematics are opened to public in a few large cities through their website, although hard copies of the schematics are available at the almost all cities. Therefore, it is necessary to digitize it by oneself in the most of the cases in Japan. Moreover, estimating spatial distribution of septic tank is more difficult than that of sewage because there is no information about its spatial distribution in most cases. Consequently, for better estimation of nutrient fluxes in suburban watersheds, there is a need to improve estimates of not only agricultural non-point sources but also point sources of effluent from domestic wastewater and livestock farming.

3. Land Use Change

The suburban zone contains new town development because of its proximity to the urban zone. The new towns are built on former agricultural land or land occupied by forest. Such urbanization increases surface runoff, by expanding the area of impervious surfaces, as well as nutrient flux. In Japan, where paddy rice is the dominant agricultural crop, urbanization inevitably causes a decline in the area of rice paddy fields. A decline in area of rice paddy fields could lead to reduced nutrient flux due to reduced amounts of fertilizer application, but could also lead to increased nutrient flux because paddies can have a nutrient removal ability as one of their multiple functions (Natsuhara, 2013). The aging of the farmer population is an issue specific to Japan that is accelerating the abandonment of paddy rice fields and freeing land for urban development.

Shimizu and Onodera (2012) performed a sensitivity test of the effect of land use change on nutrient flux in a suburban watershed using SWAT. A model calibrated using observed data had acceptable reproducibility according to Moriasi's index (Moriasi et al., 2007) and was established as the base scenario that was compared against land use change scenarios of converting rice paddy field to abandoned land, residential land, and cultivated land to achieve 5% and 10% increases in land area under that use. They found that river runoff, sediment and nutrient flux increased slightly when rice paddy field was changed to abandoned land, (Fig. 3). For increased urbanization, which represents the conversion of rice paddy fields to residential

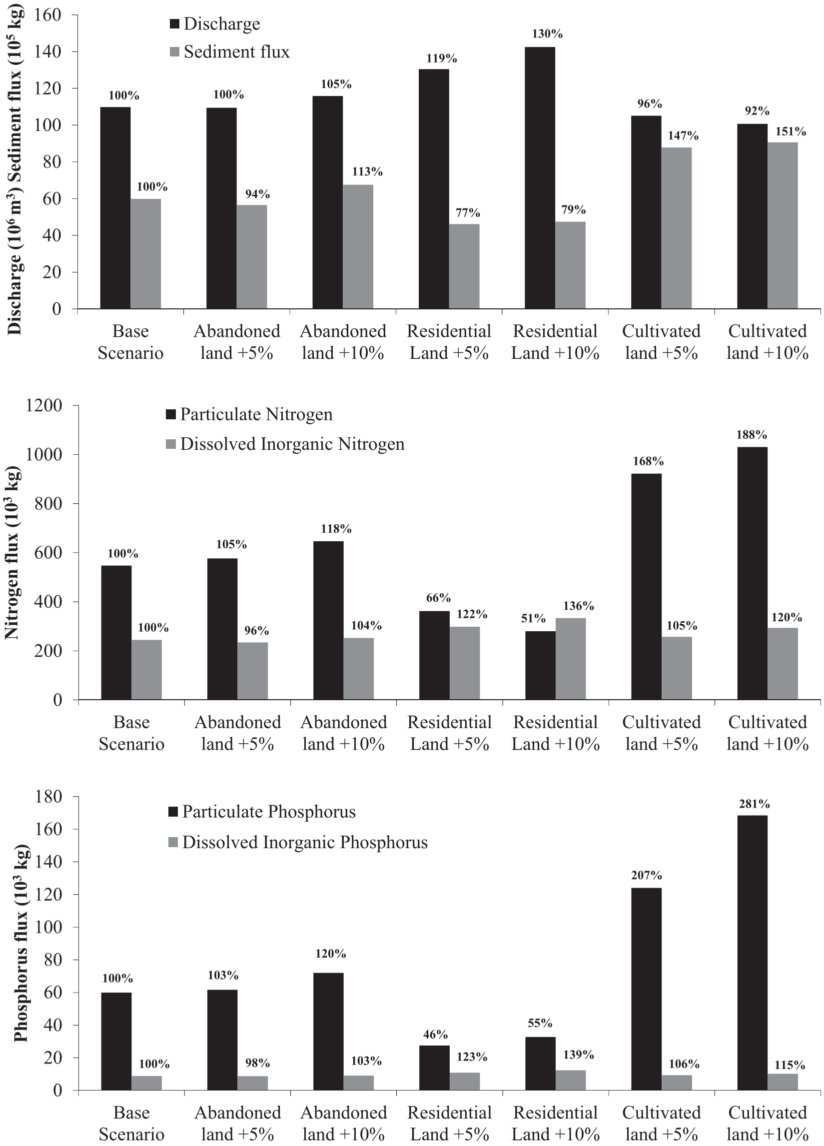

Fig. 3 Results of sensitivity analysis of land use change scenarios of converting rice paddy field to abandoned land, residential land, and cultivated land to achieve 5% and 10% increases in land area under that use. (a) discharge and sediment flux, (b) nitrogen fluxes, and (c) phosphorus fluxes. Modified from Shimizu and Onodera (2012)

land, increases were observed in river runoff, dissolved inorganic nitrogen, and DIP fluxes. Conversely, suspended solids, particulate nitrogen, and particulate phosphorus decreased. When rice paddy field was changed to cultivated land, the result was slightly decreased river runoff and DIP flux and increased suspended solids, particulate nitrogen, and particulate phosphorus fluxes. The results suggest that the effect of land use changes on nutrient flux should be considered in land use decision-making in the suburban zone because such changes are mostly unidirectional, from rice paddy field to other land use, and therefore represent a clear shift in the nutrient flux characteristics of that land. Hence, it is necessary to consider the dynamical land use changing effect such as using activating land use change module for SWAT (Pai and Saraswat, 2011) if SWAT will be applied to suburban watersheds which contain rapidly urbanizing areas.

In the meantime, the effect of decrease of rice paddy field on nutrient flux has to be considered if land use change will be discussed because rice paddy field might contribute to attenuate nutrient flux by its multiple functions. In other words, decrease of rice paddy field can accelerate the increase of nutrient flux by not only increasing domestic wastewater from residential land that is converted from rice paddy field but also weakening nutrient attenuation functions. However, it is impossible to account the attenuation effect by SWAT at present because the processes in rice paddy field have not been implemented even if the deficiencies in the original rice paddy module in SWAT have been improved by some researchers (Kang et al., 2006; Xie and Cui, 2011; Sakaguchi et al., 2014). Nevertheless, the unmodified SWAT is considered suitable for estimation of nutrient flux at the basin scale, because uncertain parameter values can be adjusted including this rice paddy effect unintentionally. Therefore, we think that SWAT can be applied to estimate nutrient flux at the watershed scale because the underlying concept of SWAT development is to allow reasonable results to be obtained at the watershed scale even if available data are scarce. However, SWAT should not be used in its original form for studies of hydrology and nutrient dynamics in rice paddy fields at the field scale. It is expected that the issue on processes in rice paddy field will be addressed during future development of SWAT.

4. Climate Change

In recent decades, global climate change such as rising air temperatures and spatial and temporal shifts in rainfall patterns have been observed (IPCC, 2007). The regime shifts induced by climate change affect nutrient and sediment fluxes because river runoff, which controls river transport capacity, is directly influenced by rainfall (Chang et al., 2001; Bouraoui et al., 2004; Andersen et al., 2006; Marshall and Randhir, 2008; Tu, 2009). Increased rainfall intensity also leads to increased soil erosion and overflows from combined sewers, which causes the discharge of untreated domestic wastewater directly into surface waters.

Studies suggest that the number of small-scale flood events may have decreased and extreme flood events may have increased in suburban watersheds. Shimizu and Onodera (2013) have suggested that in Japan flood events may have increased in magnitude and base flow periods extended based on long-term analysis of observed river runoff and SWAT estimation. Furthermore, nutrient flux is known to increase by orders of magnitude during flood periods, at least partly because nutrients from domestic wastewater tend to be accumulated within the catchment during low-flow periods for lack of transport capacity. Flood events mobilize the accumulated nutrients and transport them downstream. Therefore, flow regime shift caused by climate change may be a key driver for changes in nutrient flux on SWAT estimation in suburban watersheds.

5. Conclusion

This article provides a critical review of important factors for SWAT application that affect nutrient flux in suburban watersheds. We have discussed that domestic wastewater, land use change, and climate change could affect nutrient flux from suburban watersheds. Domestic wastewater has potentially the largest effect on nutrient flux because it is emitted every day at a constant rate. Nevertheless, domestic wastewater may have been ignored in previous studies because it is difficult to estimate compared with emissions from sewage treatment plants. Modeling of domestic wastewater involves considerable uncertainty at present owing to the limited availability of data on the volume and spatial distribution of source areas (unsewered residential development). Therefore, improving the estimation of nutrient flux in the future will involve developing better methods for estimating inputs from domestic wastewater, including by building databases of the distribution of unsewered residential areas and better characterization of the factors that affect nutrient emissions in such areas.

References

Andersen, H.E., Kronvang, B., Larsen, S.E., Hoffmann, C.C., Jensen, T.S. and Rasmussen, E.K., 2006. Climate-change impacts on hydrology and nutrients in a Danish lowland river basin, *Sci. Total Environ.,* 365: 223–237.

Arnold, J.G. and Fohrer, N., 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling, *Hydrol. Process.,* 19: 563–572.

Bouraoui, F., Grizzetti, B., Granlund, K., Rekolainen, S. and Bidoglio, G., 2004. Impact of climate change on the water cycle and nutrient losses in a Finnish catchment, *Clim. Change,* 66: 109–126.

Chang, H., Evans, B.M. and Easterling, D.R., 2001. The effects of climate change on stream flow and nutrient loading, *J. Am. Water Res. Assoc.,* 37(4): 973–985.

Fujimura, Y., 2006. Emitting value of domestic wastewater and pollutant load from several septic tanks, *J. Water Waste (Yousui to Haisui),* 48(5): 64-70 [In Japanese], available at: http://www.pref.chiba.lg.jp/wit/suishitsu/inbanuma/documents/7-seikatsuhaisuigentani.pdf.

Guse, B., Bronstert, A., Rode, M., Tetzlaff, B. and Wendland, F., 2007. Application of two phosphorus models with different complexities in a mesoscale river catchment, *Adv. Geosci.,* 11: 77–84.

Haruta, S. and Sakurai, Y., 2010. Saline concentrations in reclaimed wastewater in combined household wastewater treatment facilities for indivisual house and practical consideration of reusing the reclaimed wastewater, *J. Rural Plan. Assoc.,* 28: 357–362 [In Japanese].

House, W.A. and Denison, F.H., 2002. Total phosphorus content of river sediments in relationship to calcium, iron and organic matter concentrations, *Sci. Total Environ.,* 282-283: 341–351.

IPCC, 2007. Summary for Policymakers, In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson-Blake, L.A., Dunn, S.M., Helliwell, R.C., Skeffington, R.A., Stutter, M.I. and Wade, A.J., 2015. How well can we model stream phosphorus concentrations in agricultural catchments? *Environ. Model. Software,* 64: 31–46.

Kang, M.S., Park, S.W., Lee, J.J. and Yoo, K.H., 2006. Applying SWAT for TMDL programs to a small watershed containing rice paddy fields, *Agric. Water Man.,* 79(1): 72–92.

Marshall, E. and Randhir, T., 2008. Effect of climate change on watershed system: a regional analysis, *Clim. Change,* 89: 263–280.

Ministry of the Environment, Government of Japan, 2014. Fact-finding survey on municipal solid waste emissions and disposal in FY2013 [In Japanese], available at: http://www.env.go.jp/recycle/waste_tech/ippan/h25/index.html

Moriasi, D., Arnold, J G., Van Liew, M., Bingner, R., Harmel, R, and Veith, T., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, *Trans. ASABE,* 50(3): 885–900.

Natuhara, Y., 2013. Ecosystem services by paddy fields as substitutes of natural wetlands in Japan, *Ecol. Eng,* 542(56): 97–106.

Pai, N. and Saraswat, D., 2011. SWAT2009_LUC: a tool to activate land use change module in SWAT 2009, *Trans. ASABE,* 54(5): 1649–1658.

Richards, S., Paterson, E., Withers, P.J.A. and Stutter, M., 2016. Septic tank discharges as multi-pollutant hotspots in catchments. *Sci. Total Environ.,* 562: 854–863.

Sakaguchi, A., Eguchi, S., Kato, T., Kasuya, M., Ono, K., Miyata, A. and Tase, N., 2014. Development and evaluation of a paddy module for improving hydrological simulation in SWAT, *Agric. Water Man.,* 137: 116–122.

Shimizu, Y. and Onodera, S., 2012. Effect of climate change on nutrient discharges in suburban watershed, *Jpn. J. Limnol.,* 73: 235–254 [In Japanese].

Shimizu, Y. and Onodera, S., 2013. Effect of climate change on flood events as a major driver of nutrient transport in western Japan, *IAHS Publ.,* 359: 38–43.

Shimizu, Y., Onodera, S. and Saito, M., 2013. Applicability of SWAT model for estimation of phosphorus discharge in a suburban catchment, *J. Jpn. Soc.Hydrol. Water Res.,* 26(3): 153–173 [In Japanese].

Tu, J., 2009. Combined impact of climate and land use changes on stream flow and water quality in eastern Massachusetts, USA, *J. Hydrol.,* 379: 268–283.

Wellen, C., Kamran-Disfani, A.R. and Arhonditsis, G.B., 2015. Evaluation of the current state of distributed watershed nutrient water quality modeling, *Environ. Sci. Tech.,* 49(6): 3278–3290.

Withers, P.J.A. and Jarvie, H.P., 2008. Delivery and cycling of phosphorus in rivers: a review, *Sci. Total Environ.,* 400(1-3): 379–395.

Withers, P.J.A., Jarvie, H.P. and Stoate, C., 2011. Quantifying the impact of septic tank systems on eutrophication risk in rural headwaters, *Environ. Int.,* 37: 644–653.

Withers, P.J.A., Jordan, P., May, L., Jarvie, H.P. and Deal, N.E., 2014. Do septic tank systems pose a hidden threat to water quality? *Front. Ecol. Environ.,* 12(1): 123–130.

Xie, X. and Cui, Y., 2011. Development and test of SWAT for modeling hydrological processes in irrigation districts with paddy rice, *J. Hydrol.,* 396(1-2): 61–71.