INTRODUCTION

Rice is the staple food for almost half of the world's population. It is grown over a total area of 159 million ha with a total annual production of 685 Tg (FAO, 2010a). Rice is the largest consumer of irrigation water (Tuong et al., 2005). About 25-33% of world's fresh water is used for irrigation exclusively in rice. Rice is also one of the major nitrogen (N) users consuming about 15% of total N used in agriculture (Heffer, 2009). Excessive use of nitrogenous fertilizers in agriculture is often perceived as a common source of nitrates in soil and water systems (Singh et al., 1995; Kundu and Mandal, 2009). In addition to the 'blue baby syndrome', gastric cancer has recently been linked to high nitrate levels in drinking water. Nitrogenous fertilizers in rice fields are also considered as source of nitrous oxide, which acts as a greenhouse gas. In addition to these ecological hazards of modern agriculture, there is a huge surge in population growth. It is predicted that the global population will rise to 9.12 billion by 2050. Almost 57% of this population will reside in the Asian countries (UN, 2008) where rice is the major crop. Such a population growth would further increase fertilizer consumption to meet demand for higher production. A trend is already visible. The use of N fertilizers in Asia has increased from 46 to 62 Tg over the last decade (FAO, 2010a). Coincidentally, several studies have also shown increased detection of high levels of nitrates in groundwater systems (Chen et al., 2010; Li et al., 2010; Yang and Liu, 2010). Thus, linkage between the N use in agriculture and the global N cycle has emerged as a growing concern for sustainable development today. National Academy of Engineers (U.S.A.) has recently identified global N cycle as one of the fourteen grand challenges of engineering (NAE, 2008)

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Water requirement in lowland rice is generally high (Bouman et al., 2007a) almost 2-3 times more than that in other crops such as wheat and maize (Tuong et al., 2005). In addition to large requirement, there is a wide variation in the total water use (irrigation + rainfall) ranging from 40 cm for heavy-textured soil to more than 300 cm for coarse-textured soil (Bouman and Tuong, 2001; Cabangon et al., 2004). Tabbal et al. (2002) reported as high as 350 cm of water input in paddy fields in Philippines. More recently, Garg et al. (2009) reported that the total water input in irrigated lowland rice in the red laterite soils of eastern India during wet season may be as high as 600 cm.

High water input has a negative influence on nutrient availability and uptake by plants, causing yield reduction. Consequently, the total water productivity, defined as the grain yield per unit mass of total water applied through irrigation and rainfall, is low for paddy ranging from 0.05-1.1 g kg^{-1} as compared to 0.79-1.6 g kg^{-1} for wheat and 1.6-3.9 g kg^{-1} for maize (Tuong and Bouman, 2003). Interestingly, the water productivity with respect to consumptive water use (0.4-0.5 and 0.6-0.7 cm d^{-1} during wet and dry season, respectively) alone is comparable to that of wheat crop (Tuong et al. 2005; Zwart and Bastiaansses, 2004). This suggests that water in excess of consumptive use are due to losses through other channels. High water loss would typically involve greater loss of added agrochemicals from crop root zone leading to groundwater contamination (Castaneda and Bhuiyan, 1996; Shrestha and Ladha, 1998; Bouman et al., 2002; Kundu and Mandal, 2009).

In lowland rice, urea is the most widely used N fertilizer. Urea rapidly dissolves in water and undergoes a series of complex transformation processes producing soluble N species such as ammonium (NH_4^+-N) and nitrate (NO_3^--N) ions. All these N species may rapidly move through soil and may readily get lost from the root zone causing

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groundwater pollution (Singh et al., 1995). In fact, the N use efficiency (NUE) in rice for many N fertilizers is only in the range of 20-40% (Prasad and De Datta, 1979; Vlek and Byrnes, 1986). Such poor NUE is a growing concern for sustainable ecological health.

The use efficiencies for both water and N in lowland rice depend on the nature and properties of rice soil, the sources and quantities of applied water and N fertilizers, associated transport and transformation processes, cultural practices, and on the prevailing initial and boundary conditions in a rice field. Agricultural practices in rice fields are known to alter surface and subsurface soil conditions. For example, lowland rice is primarily grown as transplanted rice where the top soil is puddled to create a relatively impermeable layer called plow sole at a depth of 15-30 cm from soil surface (Huang et al., 2003; Garg et al., 2009). Puddling is traditionally done to reduce percolation in rice soil. Churning of top soil during puddling generally destroys soil aggregates, reduces macropores, and increases micropore volume (Moorman and Van Breemen, 1978; Sharma and De Datta, 1985). Finer soil particles in the muddy suspension get deposited at/near puddling depth to form a consolidated soil layer called plow sole between 10-25 cm soil depth (Garg et al., 2009). The saturated hydraulic conductivity (K_s) of a typical plow sole varies from 0.02-0.08 cm day^{-1} (Tuong et al., 1994; Chen and Liu, 2002; Huang et al., 2003; Tournebize et al., 2006). In addition to plow sole, small dykes (also, called as bunds) are generally constructed around paddy fields to restrict water flow horizontally through seepage. In practice, seepage and percolation are not easily separable because of the difficulty in classifying the transition between seepage and percolation (Wickham and Singh, 1978). The seepage and percolation (SP) rate may vary depending on soil properties,

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ponded water depth, groundwater level, and maintenance of field and bunds. For example, SP rate for well puddled heavy textured clay soil may range from 0.2-2.4 cm d^{-1} (Tabbal et al., 2002) compared to 29.6-68.6 cm d^{-1} in non-puddled fields containing similar type of soil (Tuong et al., 1994). Tuong et al. (1994) found that percolation rate was high in poorly puddled soil and was significantly influenced by ponded water depth. Water loss through seepage and percolation constitutes about 50-85% of total applied water in rice (Sharma et al., 2002; Singh et al., 2002).

Several researchers have suggested that the major source of SP loss in paddy fields is the bunds surrounding a rice field (Walker and Rushton, 1984; Bouman et al., 1994; Tuong et al., 1994; Kukal and Aggarwal, 2002). Higher hydraulic conductivity of soil under a bund (hereinafter, referred to as under-bund soil) than that within the rice growing area (hereinafter, referred to as within-field soil) causes water to seep into a bund (Wopereis et al., 1992; Janssen and Lennartz, 2009) and then percolate vertically down to the groundwater (Walker and Rushton, 1984; Bouman et al., 1994; Tuong et al., 1994; Janssen and Lennartz, 2008; 2009). The under-bund percolation rate may vary from 0.04 (Kukal and Aggrawal, 2002) to 3.66 cm d^{-1} (Tuong et al. 1994). Although several bund management practices such as concrete bund, gravel-packed bund, concrete-covered soil bund, and plastic-covered soil bund (Huang et al., 2003) are proposed to reduce the SP losses, most of these methods are either expensive, difficult to implement, or may have adverse effect on environment. For instance, although plastic sheets may reduce the lateral seepage by 450 mm (Bouman et al., 2005), the photocatalytic degradation of plastics is known to produce hazardous chemicals.

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Conventional urea fertilizer provides N for a period of about 4-5 days after fertilizer application (Craswell et al., 1981). One of the best management practices for urea is to split the total dose in to small amounts and apply at different crop growth stages. An alternative to this is the use of specialty fertilizers that release nutrient at slow/controlled rate to match the generally observed sigmoidal plant uptake pattern. The main purpose of such fertilizers is to improve NUE by synchronizing the crop nutrient uptake and nutrient release from fertilizers and reduce N loss by maintaining low concentration in soil-water system. However, complete check on N loss may not be possible as all the processes (release, uptake, and losses) occur simultaneously. Slow release fertilizers may restrict volatilization losses to a large extent, but runoff and leaching losses may not be entirely avoidable, specifically, under heavy rainfall or high percolation rates. Again soil characteristics and prevailing hydrology of the region would greatly influence the performance of a controlled-release source. Thus, the development of appropriate water and N management strategies based on the soil physical, hydraulic, and hydrological properties is a key step in intensive rice production system that avoids excessive N loading to the environment while ensuring desired yield.

The lateral and vertical spreading of an agrochemical depends on the physical and hydraulic properties of soil and prevalent ecohydrological conditions. A polluting source may be separated from groundwater by a poorly permeable clay layer or it may also be possible that a relatively conductive layer could connect the source with groundwater (Rao, 2006). In a typical rice soil, a good plow sole restricts percolation through the within-field area facilitating water retention inside the field. Thus, a plow sole has the potential to restrict a polluting source such as nitrate from readily moving

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into the groundwater system. On the other hand, the bunds surrounding the field may be porous and may act as a sink hole. It has been shown that higher hydraulic conductivity of under-bund soil than the within-field soil causes water to readily seep into the bund (Wopereis et al., 1992; Janssen and Lennartz, 2009) and percolate to groundwater (Walker and Rushton, 1984; Janssen and Lennartz, 2008; Janssen and Lennartz, 2009). Inasmuch as bunds around rice fields are shown as a major culprit for water loss in rice soil (Walker and Rushton, 1984; Tuong et al., 1994; Neumann et al., 2009), their contribution to transport processes and then to groundwater contamination is an important issue.

Several studies have attributed high water loss in rice soils to the development of preferential flow paths caused by cracks and crevices in plow sole (Cabangon and Tuong, 2000; Liu et al., 2003), burrows by natural fauna such as earthworms (Garg et al., 2009; Sander and Gerke, 2009), and decayed root channels (Li and Ghodrati, 1994). Recently, a series of dye tracer tests conducted to visualize preferential flow patterns in within-field (Sander and Gerke, 2007) and under-bund (Janssen and Lennartz, 2008) soil areas showed that the preferential flow can reach up to 90 to 120 cm depths within 24 hours. Similarly, season-long tracer tests conducted in lowland irrigated rice field have indicated that a tracer can reach up to 150 cm depth by flowing through the preferential path at few localize spots (Neumann et al., 2009). Hence, the preferential flow paths present in under-bund soils has the potential to connect the polluting source (nitrates in rice production system) with the groundwater system. The environmental consequence of nitrates in rice soil would, therefore, be influenced by the combined effect of under-bund and within-field soil characteristics.

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The overall objective of this study was to re-examine water and N management practices in lowland rice keeping in view the recent developments in soil hydrology. Based on the detailed review of literature, three major hypotheses were formulated. First, the rapid transport of water and solute through the preferential flow paths inside the bund soil may be responsible for the persistent detection of a short-lived chemical species such as N fertilizers in deeper soil layer. Second, a suitable mixture of coated and uncoated urea may be adapted to improve NUE. Third, proper field management practices based on soil physical and hydraulic properties may achieve improved water and N use efficiency in lowland rice. These hypotheses were examined by evaluating the following specific objectives:

- To assess the effects of selected soil physical and hydraulic properties on water flow and nitrogen transport processes in lowland rice soils
- To evaluate and compare the role of under-bund and within-field soils on water and nitrogen losses in lowland rice
- To evaluate the performance of a polymer-coated nitrogenous fertilizer for improving nitrogen use efficiency in lowland rice
- To develop a simple bund-plugging technique for improving water and nitrogen use efficiency in lowland rice

To realize these objectives, a series of field- and laboratory-scale solute transport experiments were conducted using urea as the N source. Extensive measurements were made on both within-field and under-bund soils to characterize the physical and hydraulic properties of rice soil. Resulting data were analyzed using the mechanistic models of water flow and solute transport processes in a dual-domain framework. This research led to the development of a simple bund-plugging approach to restrict water and nutrient loss through bunds around rice fields, which eventually resulted in improved water and N productivity in rice. The thesis is organized into five major

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chapters. Following a comprehensive review in Chapter 2, detailed material and methods are discussed in Chapter 3. Chapter 4 contains the results and discussion organized into four distinct sections with respect to four specific objectives. Chapter 5 summarizes the important findings of the study.

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