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Optimal nitrogen fertilizer decisions for rice farming in a cascaded tank system in Sri Lanka: An analysis using an integrated crop, hydro-nutrient and economic model

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HIGHLIGHTS

- Subsidies for fertilizer will encourage fertilizer use, but can cause health and environmental problems.
- Fertilizer decisions of rice farmers in Sri Lanka were analyzed via integrated models with a social welfare perspective.
- Social and private optimal Nitrogen fertilizer rates varied over seasons, soil types, weather and price levels.
- Application of socially optimal Nitrogen rates slightly reduces crop yields but helps in reducing water pollution.
- Social cost of fertilizer application is to be internalized in recommending optimal fertilizer rates.

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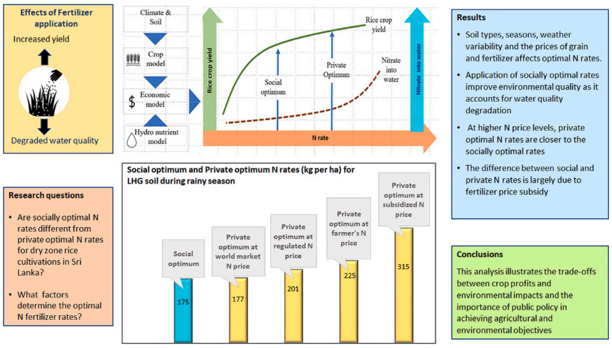
GRAPHICAL ABSTRACT



Research questions

- Are socially optimal N rates different from private optimal N rates for dry zone rice cultivations in Sri Lanka?
- What factors determine the optimal N fertilizer rates?

Results

- Soil types, seasons, weather variability and the prices of grain and fertilizer affects optimal N rates.
- Application of socially optimal rates improve environmental quality as it accounts for water quality degradation
- At higher N price levels, private optimal N rates are closer to the socially optimal rates
- The difference between social and private N rates is largely due to fertilizer price subsidy

Conclusions

This analysis illustrates the trade-offs between crop profits and environmental impacts and the importance of public policy in achieving agricultural and environmental objectives

ABSTRACT

CONTEXT: The ancient irrigation systems in Sri Lanka, known as village tank cascade systems, were developed to ensure an adequate and sustainable supply of good quality water to communities. However, there is growing concern about health and environmental issues related to the degradation of water quality caused by excessive nitrogen (N) levels from the overuse of chemical fertilizer. Subsidies for chemical fertilizer have encouraged fertilizer use for rice production in Sri Lanka.

OBJECTIVES: The objective was to evaluate the use of N fertilizers for rice production in the Thirappane cascaded tank system and its impact on nitrate water quality. An optimal rate of N use was determined based on private (farm-level) decisions on fertilizer use. However, the private optimal fertilizer rate is not adequate for overall social welfare due to market failures such as incomplete information and the lack of a market to account for the negative impact of fertilizer use on tank water quality. The hypothesis is that the social optimal fertilizer rate is lower than the private optimal rate due to this discrepancy. The study aims to identify the sources of inefficiency in the sub-optimal use of fertilizers from a social perspective.

METHOD: We developed an integrated crop, hydro-nutrient and economic model to analyze fertilizer decisions in the rice production process. The method involved conducting a marginal economic analysis based on simulated

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yield responses to N fertilizer and prices for inputs and outputs. The analysis was performed for three soil types across the *Maha* (rainy) and *Yala* (dry) seasons and for three different weather scenarios within each season.

RESULTS AND CONCLUSIONS: When the negative impact of nitrate contamination on water quality is taken into account, the optimal N fertilizer rate from a social perspective is always lower than the optimal rate determined solely by private economic considerations. These optimal rates varied based on factors such as soil type, season, weather conditions during the growing season, and fertilizer prices. At unregulated, higher, fertilizer prices, the crop yields achieved at the social optimum were only slightly lower than those achieved under the private economic optimum. However, under regulated, lower, fertilizer prices, achieving the social optimum would require a larger reduction in N fertilizer use and result in a greater decrease in crop yields.

SIGNIFICANCE: A systematic analysis that takes into account the social costs can serve as a guide for creating effective policies aimed at enhancing fertilizer decision making.

1. Introduction

The village tank cascade system, a sustainable agricultural production system in the Dry Zone of Sri Lanka in ancient times (Abeywardana et al., 2019; Leach, 1959), has been recognized as a Globally Important Agricultural Heritage System (GIAHS) by the Food and Agriculture Organization (FAO, 2018). Historically, village tank cascade systems have ensured the quantity, quality, and sustainability of water supply for rural populations (Aheeyar, 2013; Hoogesteger et al., 2023; Oyonarte et al., 2022; Ratnayake et al., 2021). They comprise low, mid and upper landscape regimes designed to maximize available water resources with varying cropping intensity, matched with the capacity of natural resources (soils and climate). The systems also helped to reduce the risk of soil erosion and nutrient losses. Traditionally, the systems were maintained by strong social organizations (led by *wel vidange*[1] under the *rajakari*[2] system practice) (Panabokke et al., 2002; Sakthivadivel, 1997). However, the village tank cascade systems have been degraded in recent years due to changes in land use, inappropriate crop management practices and abandonment of ancient management and rehabilitation practices (Ratnayake et al., 2021; Sakthivadivel et al., 1997; Sirimanna et al., 2022). The modernization of agricultural practices by use of chemical fertilizers and pesticides, and ignoring soil conservation practices, has caused a deterioration of water quality and human health in farming communities (Abeysingha et al., 2021; Young et al., 2010). This deterioration, reportedly caused by agricultural activities, has affected the ecology of the tanks and human health in the farming community (Abeysingha et al., 2021; Dharma-Wardana et al., 2015). Thus an interest in the rehabilitation and reconstruction of the system has been growing among government and non-government agencies (UNDP, 2017). A recent study found that immediate actions are needed concerning proper land use planning, farmer awareness and integrated nutrient management in the cascades to minimize external pressures (Wickramasinghe et al., 2023). Kulasinghe and Dharmakeerthi (2022) recommended that land-use policies and input management need to be changed to ensure the sustainability of village tank cascade systems.

A Government fertilizer subsidy policy has been the main instrument of agricultural support in Sri Lanka. The policy was initiated in 1962 following introducion of high-yielding crop varieties (HYV) associated with the Green Revolution. Higher fertilizer use and irrigation were needed for HYVs to achieve their yield potential. The introduction of the subsidy policy aimed to enhance crop productivity by promoting fertilizer application at the levels recommended by the Department of Agriculture at a low cost (Weerahewa et al., 2010). The fertilizer policy has been adjusted periodically in response to fluctuations in global fertilizer prices and pressures on Government expenditure. In 2018 and 2019 chemical fertilizer for rice farming was subsidized by 85% (the regulated price of urea fertilizer was 3.09 US$ per 50 kg bag, and the non-regulated price was 21.30 US$ per 50 kg bag in *Yala*[3] and *Maha*[4] seasons, the Government subsidy was 18.21 US$ per 50 kg bag in 2018). In *Yala* in 2020, chemical fertilizer was provided free of charge. The importation of chemical fertilizer was abolished entirely on May 06, 2021, and this decision was rescinded on November 30, 2021 (Ministry of Finance, 2019, 2020, 2021). Overall, the fertilizer subsidy policy has successfully increased agricultural productivity in Sri Lanka. However, it is important to consider the potential negative impacts of the policy, such as environmental damage and unequal distribution of benefits.

Nitrate is a common pollutant in both surface and groundwater that comes from a variety of sources, including agricultural runoff, sewage, and industrial waste, and excessive levels can lead to exceedance of permissible limits for water quality. Nitrate can readily move down the root zone in agricultural soils and reach the groundwater (Pretty et al., 2000; Tilman, 1999) and is often associated with eutrophication (Cecchin et al., 2021; Le et al., 2010; Tilman et al., 2002) and health issues (Ramalingam et al., 2022; Ward et al., 2018). Assessment of agricultural practices regarding N fertilizer use is essential in considering water quality-related issues in agricultural systems (Agouridis et al., 2005; Gibbons et al., 2005). Many studies have demonstrated the variability in fertilizer rates across soil types (Link et al., 2006; Morris et al., 2018). However, weather variability during the cropping season has been neglected (Bert et al., 2006; Lehmann et al., 2013; Monjardino et al., 2013). This variability affects crop yield, crop N demand and nitrate losses to the environment. Growing season rainfall influences soil water and nutrient cycling, which contributes to N supply to the crop (Hochman and Waldner, 2020) and N losses to the environment (Hyytiäinen et al., 2011; Miller et al., 2020). Further, Ranasinghe et al. (2023) emphasize that farmers must take adaptive measures against climate change to gain from the abundant natural resources in the cascades. However, apart from these influencing technical factors of farming, other compelling economic factors, including input and output prices and government policies, are also important in fertilizer decisions and environmental outcomes (Kuhn et al., 2020; Sihvonen et al., 2021; Yu et al., 2022).

Studies addressing the application of economic theory for non-point pollution control have used combined biophysical and economic models to address the complexity of relationships between agriculture and the environment (Doole et al., 2013; Knowling et al., 2020; Kruseman et al., 2020; Ramilan et al., 2011). Few studies have included the spatial dimension or used social costs in decision-making (Lesschen et al., 2005; Zhao et al., 2006). We include a factor to account for the social cost of N (SCN) in the decision framework. Systematic analysis can overcome the

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[1] *Wel vidange* is the person appointed by the farming community as the offical in-charge of the management of the village tank cascade system

[2] *Rajakari* system was the traditional system of land tenure in Sri Lanka until the early 19th century where land was granted in exchange for services rendered. The services expected were of two kinds: (1) public works, such as road and bridge building or, in earlier days, the construction of irrigation works, and (2) special services elicited on the basis of a person's caste-related occupation.

[3] *Maha* (wet) season which is observed during October to March receives rainfall from the North-East monsoon

[4] *Yala* (dry) season which is observed during April to September receives rainfall from the South-West monsoon.

deficiencies of decision analysis and provide information about the inplications of including social costs associated with those decisions (Mallawaarachchi et al., 2002; Mallawaarachchi and Quiggin, 2001).

This paper aims to explore the sources and magnitude of inefficiency associated with sub-optimal fertilizer use within the concept of market failure. This causes a divergence between N fertilizer rates for an individual deciding on actions under incomplete information (private benefit) and that of society (social benefit). The latter fertilizer rates are often lower as a society must bear the burden of inefficiency.

This study uses the simulation of crop yield responses and nitrate losses from rice fields in a village tank cascade in Sri Lanka to determine the spatially targeted optimal N fertilizer rates. This approach aims to understand the factors (both technical: soil type, season, weather, and economic: the price of grain, price of fertilizer, the social cost of pollution, and government policies) influencing N fertilizer decisions for rice production and associated trade-offs between agricultural production and the water quality in the cascade tanks.

We hypothesize that operating at a 'socially optimal N rate' leads to substantial yield and profit losses compared to a 'privately optimal N rate'. Thus the analysis is pursued by accounting for factors influencing the nature of trade-offs by developing integrated crop, hydro-nutrient and economic models for the Thirappane tank cascade of Sri Lanka. We follow Gourevitch et al. (2018), who defined the socially optimum N rate as the rate at which net benefits of N to society are maximized. The private optimum N rate was defined as the rate of N that maximizes the private net benefits only to the farmer.

2. Materials and methods

2.1. The study area

The study is conducted in the Thirappane tank cascade, located in the North Central province of Sri Lanka. The cascade comprises a series of six minor tanks each with less than 50 ha command area and a total water holding capacity of 1,988,373 m^3 (Fig. 1). The distance between the uppermost (8.15 N, 80.52 E) and the lowermost tank (8.21 N, 80.51 E) is eight km, and the cascade is two km wide. The total cultivation area is 207 ha. The command area of the tanks is relatively flat (maximum slope of 3%) (Jayatilaka, 2001). These minor tanks are mostly seasonal in nature, and maintenance is conducted with the support of farmers. The tanks and their characteristics are listed in the Supplementary Table S1. In accordance with government regulation,[5] only rice (*Oryza sativa*) can be cultivated in the lowlands of Sri Lanka when water is available in sufficient quantities.

Three major soil types are present in the cascade: namely, Low Humic Gley (LHG) poorly drained soil, Reddish Brown Earth (RBE) imperfectly drained soil, and RBE well-drained soil (Fig. 1). RBE is the predominant soil type covering 75% of the total land area; however, LHG soil is predominant in rice cultivation areas. Tank water is used for the irrigation of rice, as well as for domestic activities, such as bathing, washing, and drinking. Occasionally, tank water is also used for livestock, such as cattle, buffaloes, and goats. Tank water is also sometimes used for fish farming, which is an important source of income for many farmers. Tank water is used for recreational activities, such as swimming and boating. Rainfall is received in a bi-modal pattern, where 70% of annual rainfall (on average 1490 mm) is received in the *Maha* season, and nutrient levels in the tanks follow the rainfall pattern (Wijesundara et al., 2013).

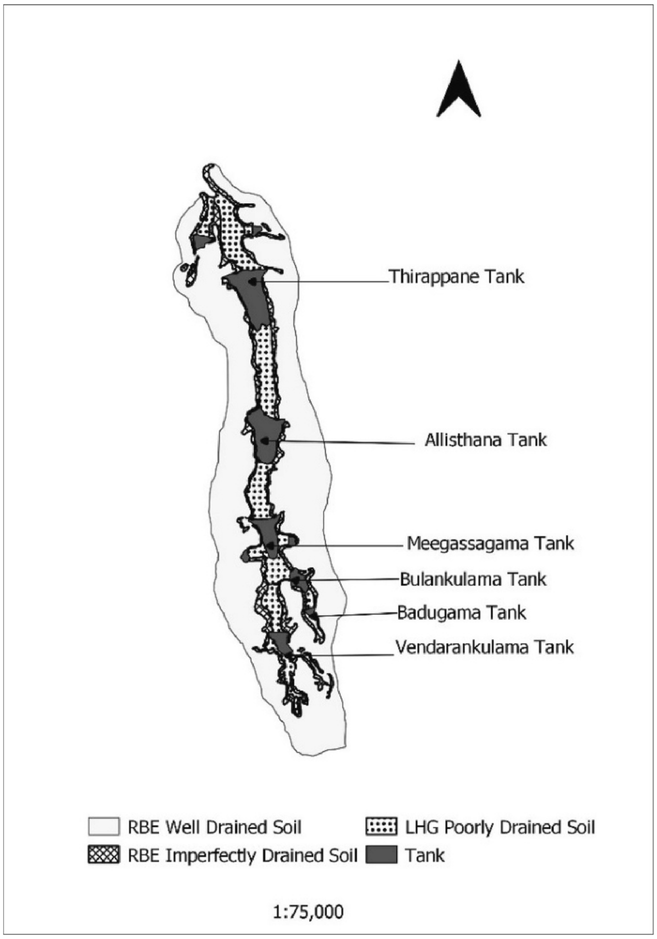

Fig. 1. Map of the Thirappane cascade illustrating the structure and the distribution of the soil types.
Note: The water flows from the upper stream tank (Vendarankulama) to the lower stream tank (Thirappne).

Nutrient use in crop production within the cascade has increased the concentration of nutrients in tank water, mainly nitrate and phosphate. The downstream tank (Thirappane) has an elevated concentration of nitrate compared to other tanks in the cascade, illustrating the spatial accumulation of nitrate down the tank cascade (Wijesundara et al., 2012). This tank shows algal blooms in some months of the year (Zoysa and Weerasinghe, 2016). A study by Abeysingha et al. (2021) showed that the nutrients in water within the cascade had reached the eutrophic level with possible environmental and health impacts.

2.2. Modelling approach

An integrated modelling framework was developed and applied (Fig. 2) to derive optimum N fertilizer rates, which maximize the social benefits and private profits of rice farming constrained by nitrate levels in tank water. Socially optimal N rates were calculated using crop production and nitrate transport functions, including the social cost of N (SCN) and prices of rice and fertilizer. Privately optimal N rates were calculated using crop production functions and prices for rice and fertilizer.

A systematic analysis was undertaken by developing and integrating three models: a crop simulation model for yield responses, nitrate leaching, and runoff from the rice fields as a function of N fertilizer applied; a hydro-nutrient model to predict the nitrate transport into tanks from the rice cultivation areas with flow paths of nitrate leaching, runoff and lateral flow; and an economic model to estimate socially and

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[5] The Agrarian Development Act (2000) restricts cultivation of paddy land, from which the maximum production can be obtained, to only rice, with powers to prescribe paddy lands vested in the Land Commissioner-General (LCG) under the Paddy Lands Act (1958), which was later replaced by the Agricultural Lands Law (1973) and also extended to uplands. Several deviations were allowed with written permission of the LCG.

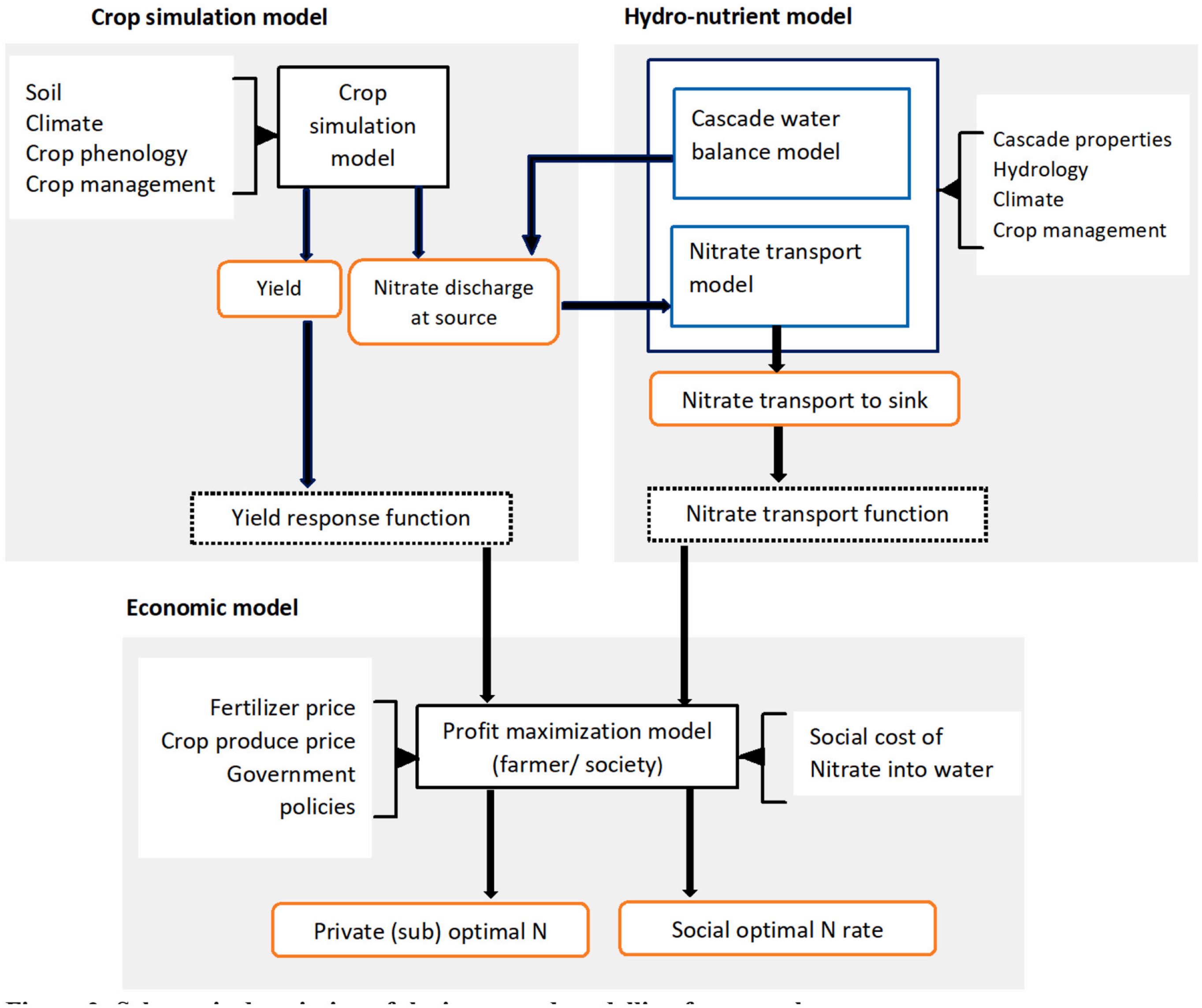

Fig. 2. Schematic description of the integrated modelling framework.

privately optimal N levels by maximizing social benefits and private profits respectively after accounting for soil heterogeneity, weather variability over and within seasons, effects of fertilizer subsidies and other policies, and the effects on society of reduced tank water quality. The framework can be used to inform policy decisions on N fertilizer subsidies and other policies related to N fertilizer use in rice farming.

2.2.1. *Data*

Socio-demographic, economic and physical data were sourced from a farm household survey conducted in the study area in 2019 (Kanthilanka, 2022) using a structured questionnaire which included questions on farm household characteristics, agricultural production activities, agricultural lands, farm assets, nutrient management (N, P and K), weed control, irrigation, labour use, crop harvest, other income sources of farmers, and farmer perceptions of water quality and functioning within the Thirappane tank cascade. A historical series of climate data were available from the closest meteorological station located at Mahaillupallama, representing the current climate of Thirappane. Secondary data, including sowing dates, area of cultivation and fertilizer quantity provided under subsidy, were collected from the Department of Agrarian Service Centre records at Thirappane. The reported district average rice yields were obtained from the Department of Census and Statistics of Sri Lanka for the *Yala* and *Maha* seasons from 1997 to 2018. Average fertilizer usage data was obtained from the National Fertilizer Secretariat of Sri Lanka.

2.2.2. *Crop simulation model*

Rice yield and soil N dynamics were simulated using the Agricultural Production Systems sIMulator (APSIM) (www.apsim.info) version 7.10. APSIM was used to simulate grain yields, nitrate leaching, and runoff of a typical rice cropping system under a 32-year series of historical climate data to account for yield variability induced by inter-annual climate variations.

2.2.2.1. Model calibration. The model was calibrated using management data. The calibration process involved adjusting the parameters of the model to match the observed crop growth and yield at the study location. The management data was collected through a household survey for the main crop production seasons in 2018 and used to calibrate the crop simulation model. The most common rice varieties cultivated in *Maha* were “BG 359” and in *Yala* “BG 300”. Both are HYVs. The BG 359 variety has a 3.5-month growing period and BG 300 has a three-month growing period. The phenological parameters for commonly grown rice varieties were obtained from Amarasingha et al. (2015), as shown in

Supplementary Table S2. Soil layer characteristics of the study area were also obtained from Mapa and Pathmarajah (1995) and Mapa (2020). The soil characteristics are summarized in Supplementary Tables S3-S5. A historical series of climate data for yield simulations was available from the meteorological station located at Mahaillupallama. Climatic datasets cover 1976–2019 and include daily values of rainfall, temperatures, relative humidity, wind speed and sunshine duration (used to estimate solar radiation). Daily incoming radiation ($MJm^{-2}d^{-1}$) was calculated using sunshine hours, latitude and longitude and angstrom coefficient ($a = 0.29$, and $b = 0.39$) (Samuel, 1991). The model was configured for soil being puddled and levelled. Direct seeding was implemented at 90 plants/m^2 density. A seven-day sowing window was used in the simulations. Depending on the rainfall distribution, crop water requirements were supplemented through irrigation during the growing period. The irrigation water used was considered later in the hydro-nutrient modelling. N fertilizer applications were simulated according to farmer practice in the cascade.

2.2.2.2. Model validation. The model was validated at temporal and regional scales. The reported district average rice yields were obtained from the Department of Census and Statistics of Sri Lanka for the *Yala* and *Maha* seasons from 1997 to 2018 and were compared with the APSIM simulated yield in LHG soil for average N fertilizer use in respective years. Average N fertilizer usage data was obtained from the National Fertilizer Secretariat of Sri Lanka. The average N application rates ranged from 60 to 150 N kg/ha from 1997 to 2018 in the Anuradhapura district.

As the regional scale model validation, the simulated rice yields for farmers' N fertilizer use at the cascade for 2018 were compared with observed farm yields collected from the household survey conducted at the cascade in 2019. The model performance was evaluated using the root mean square error (RMSE) (Pham, 2019).

2.2.2.3. Model simulation. The validated model was used to estimate long-term rice-yield responses, nitrate leaching and nitrate runoff for different levels of N fertilizer applications using weather data from 1976 to 2019. Simulations were conducted for all three soil types in the *Maha* season. Rice cultivation was restricted to LHG poorly drained soil and RBE imperfectly drained soil in the *Yala* season. There was always a restriction on the area of rice cultivated in *Yala* due to limited irrigation water availability in the tanks (Warnakulasooriya and Shantha, 2021). Initial N application rates varied from 0 to 300 kg per ha per season (100% increase of current mean application at the cascade in 2018) per ha per season to identify the general trend of yield and nitrate-discharge responses.

2.2.3. Hydro-nutrient modelling

The hydrological model was a node-link network in which nodes represent physical units (tanks) and links represent the connection between these units. The hydro-nutrient model comprised two sub-models: a water balance model and a nutrient transport model. Total daily nitrate discharged (including leaching, runoff and lateral flow) from the cultivation area in the source tank and transported into the sink tank was simulated from 1997 to 2019 and summed annually for *Maha* and *Yala* seasons across all soil types. The water balance model simulated the water flow between tanks, and the nutrient transport model simulated the transport of nitrate from the source tank to the sink tank. The model was calibrated using observed data from the tanks and the surrounding area. The model was used to simulate the hydrological and nutrient transport processes in the tank cascade system.

2.2.3.1. Water Balance model. Many previous studies have developed and used a particular water balance model for the Thirappane tank cascade (Itakura, 1995; Itakura and Abernethy, 1993; Jayatilaka et al., 2003; Oka et al., 2019; Shinogi, 1998). We adopted that model, which had already been calibrated for the study area. The cascade water balance model was formulated based on a simple structure, incorporating the dynamic hydrologic processes associated with a set of tanks in the Thirappane tank cascade. The model considered all inflows and outflows of water in a tank in the cascade. Inflows and outflows varied with the position of the tank in the node-link representation. After defining the inflow and outflow for each tank, the water balance was estimated daily (according to equations given in Supplementary Eqs. S1 to S11). Each tank's irrigation water supply potential was estimated based on crop water requirements after accounting for conveyance losses. Based on this, the maximum possible areas of cultivation for the *Yala* and *Maha* seasons were determined and used in the modelling. For agricultural non-point source pollution, the process can be divided into the “source” link of field pollution generation and the “sink” link of water transportation through drainage channels (Wan et al., 2021; Wriedt and Rode, 2006). We also used the source-sink linkage in modelling nitrate transport.

2.2.3.2. Nutrient transport model. The nutrient transport model consisted of export coefficients for nitrates from the field on the assumption that land-use changes, including fertilizer decisions, are a major determinant of nitrate occurrence in the catchment (Johnes et al., 2007; Worrall and Burt, 1999; Zhang et al., 2019). Some components of this model have been developed with inputs from Neitsch et al. (2011) in SWAT as adapted by Lam et al. (2010). The nitrate transported in each path was estimated via a set of equations adapted from the SWAT (Neitsch et al., 2011) (see Supplementary eqs. S6 to S10).

The nutrient transport model was coupled with the water balance model to evaluate nitrate movements within the cascade for different rates of N applications in the cultivation area in the source tank. The amount of nitrate transported into the sink tank via each flow path, including leaching, runoff and lateral flow, was estimated as the product of the volume of water and the average concentration of nitrate in each soil layer (Lam et al., 2010). The export coefficients used were those in the water balance model (see Supplementary Table S6).

2.2.3.3. Model validation and simulations. Daily tank water height data collected from April 2013 to 2015 by Oka et al. (2019) were used to calibrate and validate the cascade water balance model. The validated model was used to simulate tank water balance and nitrate transport from 1997 to 2019 for five N rates (for *Maha* season 0, 50, 100, 150 and 200 kg N/ha and for *Yala* season 0, 30, 60, 90 and 120 kg N/ha). All simulation analyses were modelled on a daily-time-step basis, and a seasonal total of variables was obtained where needed. Finally, nitrate transport functions were estimated for each soil type, season, and tank combination.

2.2.4. Economic modelling: Production function approach with profit maximization

Rice yields and nitrate discharges from the soil responding to fertilizer applications were developed from crop simulations and are presented in the results section. Conceptually, as the N fertilizer rate increases, crop yields increase at a decreasing rate and nitrate discharges from the soil increase at an increasing rate.

Diminishing return responses are common in biology, ecology and animal production (Thornley and France, 2007). A modified Mitscherlich-Baule (Brorsen and Richter, 2012) yield response function was fitted for the relationship between N rate (x) and grain yield (Y) for each scenario,

$$Y = a + b\left(1 - e^{-kx}\right). \tag{1}$$

In eq. (1), Y is rice yield (t/ha), a is the yield at zero fertilizer application (t/ha), b is the parameter above a where yield increases to the asymptote, k is a coefficient of gain, and x is the rate of N application (kg/ha). The level of asymptotic yield is given by $a + b$.

Gourevitch et al. (2018) determined the socially optimum rates of N fertilizer application by evaluating the private and social costs and benefits of N and identified the rate to maximize the net benefits of N to society. Keeler et al. (2016) investigated the SCN by quantifying the damage costs of N to air, water and climate.

A framework, including an estimate of the SCN for water quality, was adopted to develop a socially optimum rate of N. The concept of a socially optimum fertilizer rate depends on the availability of complete information about underlying natural processes, the effects of government policies, and whether there are distorted or missing markets. Uncertainties about underlying natural processes include crop yields and nitrate losses arising from differing N fertilizer rates (depending on seasonal factors) and knowledge about nitrate transport from fields to tanks for differing N fertilizer rates. Policy distortions include subsidized fertilizer inputs, the fact that fertilizer is a regulated import, and land use restrictions for where and when rice is grown. No clearly defined community property rights are associated with acceptable water quality for human consumption.

The decision framework is presented (Fig. 3) to conceptualize N fertilizer use from social and private viewpoints. This accounts for the missing information, a lack of property rights, and distortions associated with the N fertilizer policy in Sri Lanka. The framework explicitly addresses input price uncertainties arising from the fertilizer subsidy policy and the social cost of adverse tank water quality. The framework provides a decision-making tool for farmers and policymakers to evaluate the optimal N fertilizer rate for a given crop and subsidy scenario. The framework also provides a basis for evaluating the effects of within-season variability in crop yields and nitrate transport on optimal fertilizer decisions. The framework can be used to evaluate the effects of alternative fertilizer subsidy policies on optimal N fertilizer rates and the associated economic and environmental impacts.

Arising from the diminishing returns, crop yield responses encapsulated in the Mitscherlich-Baule functional form and including crop input and output prices, the analysis proceeded by developing a marginal value product (MVP) schedule, which typically declines as the N fertilizer input increases (Dillon and Anderson, 1990; Anderson et al., 1977)). Input prices, expressed as marginal costs (MC), are included to develop optimal N fertilizer rates where the marginal benefit (MVP) equals the MFC. In this analysis, the input prices include alternative fertilizer prices for various subsidy scenarios and an assumed social cost associated with reduced tank water quality.

These scenarios address the market failure issues of distorted input prices and the inclusion of community property rights associated with acceptable water quality for human consumption. The framework does not address other effects of market failure associated with using N fertilizer for rice production in Sri Lanka (e.g., nitrous oxide emissions contributing to global warming potential).

In Fig. 3, N_s is the social optimum N rate and N_{P1}, N_{P2}, N_{P3}, and N_{P4} are defined as sub-optimal N rates with different N prices. Ns was determined at the marginal social cost of nitrogen (M_SCN), which included the damage cost of nitrate-N into the water (SCN) and the world market price of N fertilizer (P_{N_W}). The world market price of N is shown at N_{P1}. At N_{P2}, the regulated market price of N (P_{N_RM}) in Sri Lanka is considered. The N_{P3} sub-optimal N rate is a ‘farmer's price (P_{N_av}), which is included because paddy farmers can purchase N fertilizer from the market or from other farmers at a rate lower than the regulated market price and higher than the subsidized price. In practice, this happens. The N_{P4} sub-optimal N rate is in the absence of a quantity restriction with a subsidized price (P_{N_S}). This is a hypothetical scenario, as only a quota of fertilizer is provided at a subsidized rate (see Table 1).

Damage cost estimates for nitrate-N in water are not available specifically for Sri Lanka. Hence, an estimate from China (Yin et al., 2019) was adapted for this study for illustrative purposes. The analysis estimated the nitrate transported; then nitrate was converted into nitrate-N by multiplying by 0.226 (N accounts for 22.6% of the nitrate ion). The damage cost of nitrate-N used in the study was US$ 1.32 per kg of nitrate-N in the water. This includes health and environmental costs. The damage cost was converted into Sri Lankan rupees using the exchange rate in 2018 (1 US$ = LKR.161.81). The social and private economic N rates were sensitive to input and output prices. We fixed the rice grain price at 0.25 US$/kg (in 2018) in the analysis.

The high, low and medium profit potential years were identified via cumulative probabilities of yield (Farquharson, 2006) and net return (Kandulu et al., 2018; Kandulu et al., 2012). We used three simulated yield-outcome categories for growing season weather variability, low (10th percentile of yield), medium (50th percentile of yield) and high (90th percentile of yield).

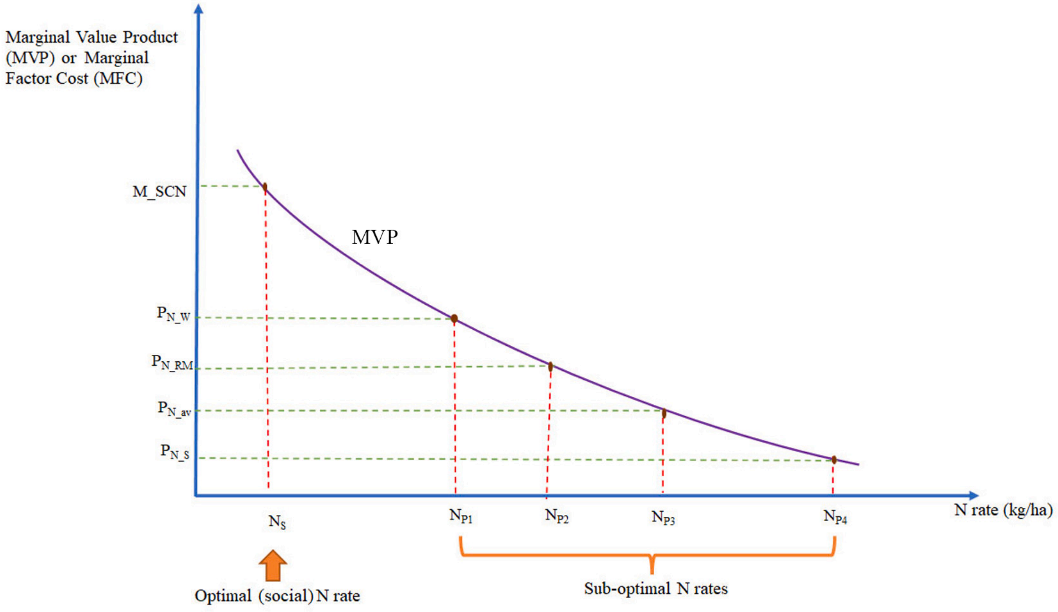

Fig. 3. Decision framework developed for optimal fertilizer rates for alternative N fertilizer prices includes subsidized price (P_{N_S}), farmers' price(P_{N_AV}), regulated market price (P_{N_RM}), and world market price (P_{N_W}). The optimal (social) N rate is decided at the marginal social cost of N (M-SCN), including the damage cost and world market price of N.

Table 1
Price details associated with the decision framework cited in Fig. 3.

Prices	Details	Price of N	
		LKR/kg	**US$/kg**
World Market price (P_{N_W})	World market equivalent price in 2018. Not paid by farmers.	152	0.94
Subsidized price (P_{N_S})	Prior to 2021, a price subsidy was provided up to the quota level of 86 kg of N/ha.	22	0.14
Regulated Market price (P_{N_RM})	The market price paid by farmers for N over and above 86 kg of N/ha. Government funded the gap between P_{N_W} and P_{N_RM}	109	0.67
Farmers' price (P_{N_av})	The weighted average of subsidized and regulated market prices. Specific for seasons according to average N usage[a]	78 in *Maha* 76 in *Yala*	0.48 in *Maha* 0.47 in *Yala*
Damage cost of nitrate-N (SCN)	Based on Yin et al. (2019)	213.59	1.32

LKR is Sri Lankan Rupees, and the exchange rate in 2018 was 161.81 LKR/US$.

[a] The average N usage per ha per seasons in 2018 in the Thirappane Cascade, data gathered from the survey.

3. Results and discussions

The results presented here focus on the LHG poorly drained soil (over 75% are distributed in the cultivation lands) and the main season used for rice production (*Maha*). The complete set of results is in the Supplementary materials.

3.1. Crop simulations

The parametrized and validated APSIM Oryza model was used to simulate long-term (1976 to 2019) seasonal rice yield and nitrate discharge via leaching and runoff in all three soil types (for model validation, see Supplementary Figs. S1, S2, S3, and Tables S7 and S8). The present study identified the impact of the rate of N fertilizer on rice yield and nitrate discharge via leaching, runoff, and lateral flow while accounting for variability in weather and soils.

3.1.1. Variability of rice yield over the season, soil and weather

Simulated rice yields for increased N rates showed general increases at a decreasing rate up to a plateau in all soil types (Fig. 4). The rate of yield increase for N applications varied between soil types. The highest median yield response for applied N was observed in LHG poorly drained soil, while the lowest was in RBE well-drained soil. As expected, the yield simulated at each level of N was stochastic due to climate variation over the years. In general, there was a lower variation in simulated rice yield in LHG than in other soils over the years. The poor drainage condition (lower saturated hydraulic conductivity) of LHG soil increases its ability to retain water and N, making more of them available for rice plant growth. The simulated yields over soil types in both *Yala* and *Maha* are shown in Supplementary Fig. S4.

3.2. Nitrate load simulations

3.2.1. Simulations and validations of water flow

The results of this study suggest that the model could accurately simulate the water volume of the tanks. The observed and simulated water volume of the tanks showed good agreement (Fig. 5). The RMSE of each tank was Vendarankulama 23 (m^3 ‘000), Bulankulama 17 (m^3 ‘000), Meegassagama 82 (m^3 ‘000), and Allisthana 93(m^3 ‘000). A close match between the observed and predicted water volumes indicated that the model could capture the hydrological dynamics of the tanks. Similar model validation was observed in studies by Jayatilaka et al. (2003), Fujihara et al. (2011) and Tan et al. (2018).

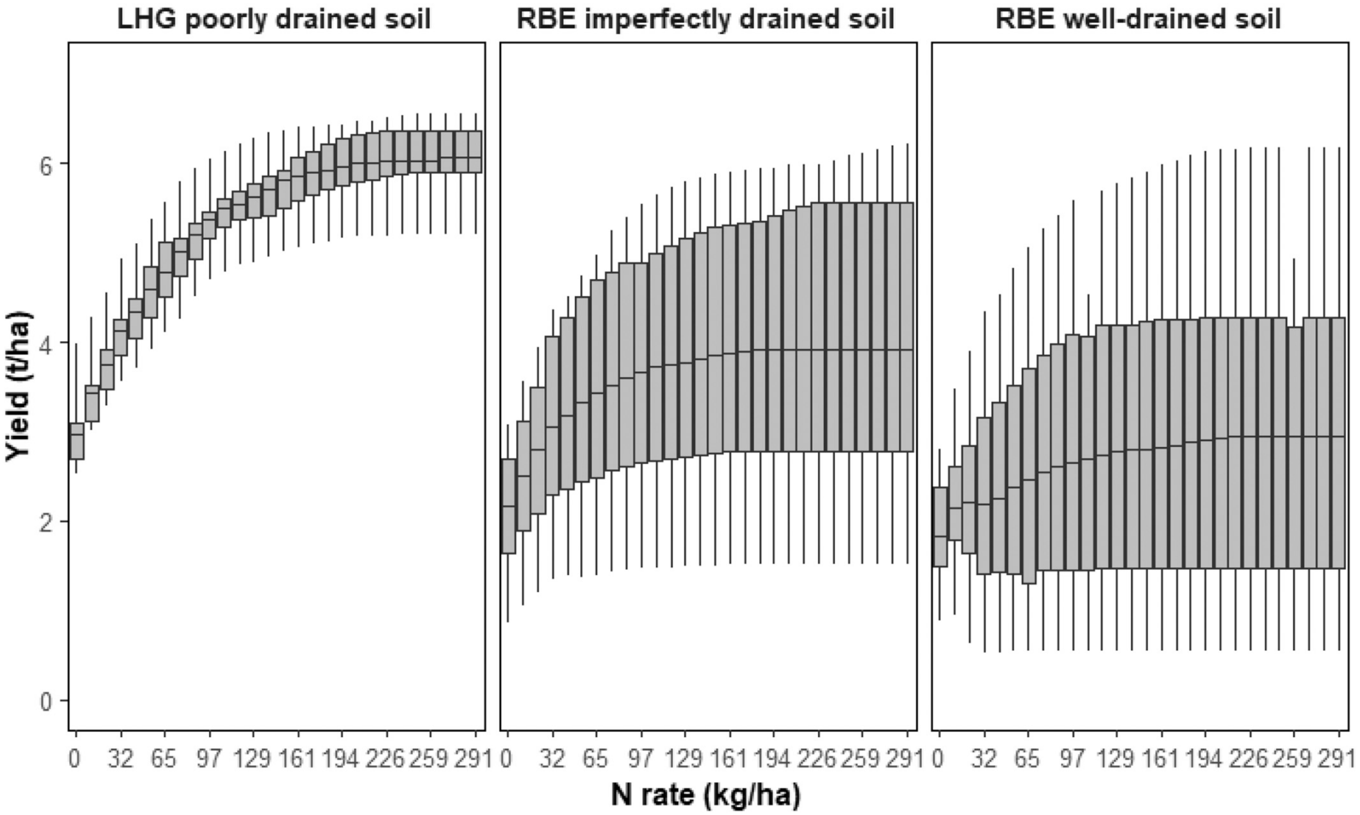

Fig. 4. Distribution of APSIM simulated rice yield from 1976 to 2019 for varying fertilizer application levels in the *Maha* season for all soil types at the Thirappane tank cascade.

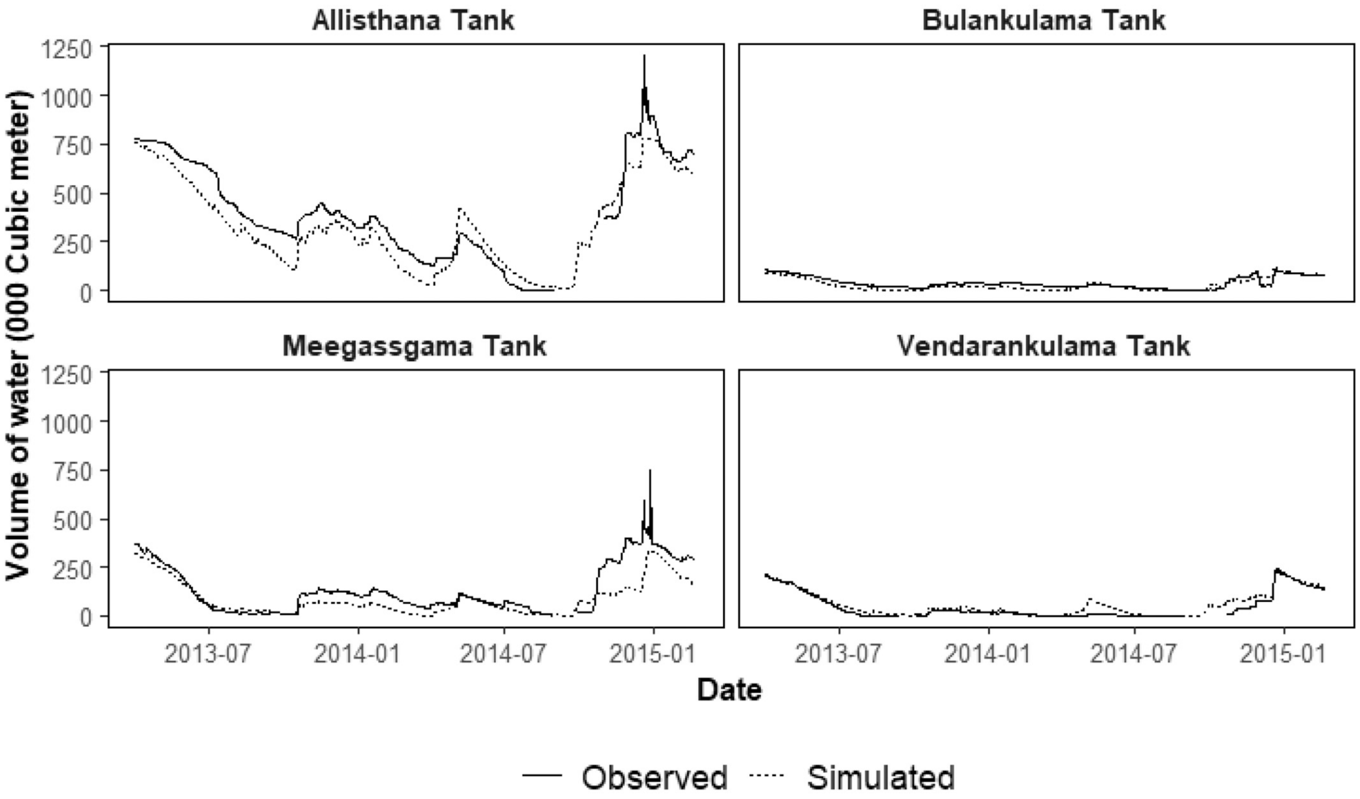

Fig. 5. Model validation with observed and simulated daily water volume in the tanks at the Thirappane tank cascade for the calibration period.

The average inflow and outflow contributions within the season were variable (Supplementary Table S9). Runoff from the catchment was the main inflow component in each tank in both seasons, from 60 to 75% in *Maha* and 50 to 88% in *Yala*. Seepage was the main outflow component in any tank, accounting for 30 to 60% of outflow in *Maha* and 50 to 85% in *Yala*. Water issued for irrigating rice crops was the second-highest outflow component from a tank at the cascade. As a sink of nitrate, the return flows from the source tank are very important since the N fertilizer applications directly influence the flow path in the rice cultivation fields. Nitrate was carried from the return flows, including seepage (leached nitrate) and irrigation water issue (nitrate runoff). Around 2 to 5% of inflow in the *Maha* season consisted of water issue return, while in the *Yala* season, it was 4 to 10%. The seepage return contribution was 2 to 8% and 20 to 32% in *Maha* and *Yala*, respectively (see Supplementary Table S9).

3.2.2. Nitrate discharge at fields and transport into tanks

Simulated Nitrate discharges, including leaching, runoff and lateral

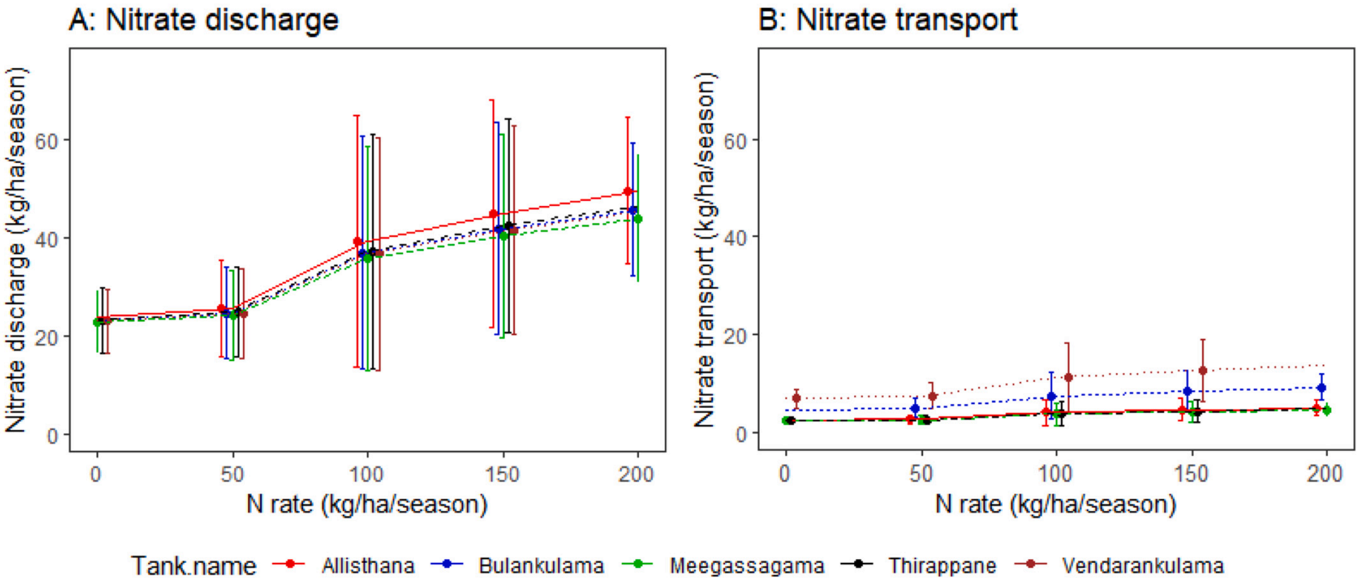

Fig. 6. Mean nitrate discharge from the cultivation area in tank (A) and mean nitrate transport into the sink tank (B) for different rates of N application in LHG poorly drained soil for the *Maha* season at the Thirappane cascade. (error bar represents the standard deviation of nitrate discharge and transport at respective N level.

flows, were positively related to N applications for all soil types (see Fig. 6A). Mean nitrate discharge at the cultivation fields in the source tank within the season ranged from 22 to 50 kg/ha in LHG soil in the *Maha* season. The higher discharge of nitrate at higher N rates can be justified by the findings of Craswell (2021) that current crops use no more than 50% of N fertilizer applied. The discharge of nitrate from cultivation fields is a soil-specific characteristic which did not vary much between tanks in the cascade (see Supplementary Figs. S5 & S6 for more results).

Other studies have frequently reported the coupling of nitrate and water movements (Chowdary et al., 2004; Mack et al., 2005; Sagehashi et al., 2016; Zhang et al., 2020). We have followed the same procedure, with the export coefficients used in nitrate transport modelling being 0.1 to 0.3 for the study area, which was within the range of reported values in other studies (Dash et al., 2015; Parashar et al., 1998).

As expected, nitrate transport was positively related to the rate of N applications (Fig. 6B). Mean nitrate transport into the immediate sink tank within the season ranged from 3 to 5 kg/ha in LHG soil. However, as indicated in Supplementary Fig. S6, nitrate transport differences were observed between tanks. Ten percent of nitrate discharges from cultivation areas in the source tanks of Allisthana tank and Meegassagama tank were transported into the sink tanks (into Thirappane tank and Allisthana tank, respectively). Twenty percent and 30% of nitrate discharge in cultivation areas of the Bulankulama tank and Vendarankulama tank were transported into the sink tank (Meegassagama tank), respectively. The Vendarankulama and Bulankulama tanks showed comparably higher nitrate transported into the lower tank than other tanks. Both those tanks are sinks to the Meegassagama tank. The nitrate transport rate was higher in the Bulankulama and Vendarankulama tank than in the other tanks. This could be due to the higher slope of the cultivating fields in these tanks, compared to other tanks, which increases the nitrate transport rate.

Using the simulated nitrate transport data, the nitrate transport functions have been estimated and the findings are presented in Table 2 for LHG soil in the *Maha* season (see Supplementary Table S10 for coefficients for other seasons). The estimated coefficients reveal that the N application rate significantly positively impacted the amount of nitrate transported into the sink tank from the cultivation area in the source tank in LHG soil in *Maha* (see Table 2). Our findings are consistent with other studies, which demonstrated an exponential increase in N discharge for small increases in N input based on field measurements (Delin and Stenberg, 2014; Jiang et al., 2017; Tan et al., 2018). In conclusion, nitrate transport was positively related to the rate of N applications and was also affected by the slope of the cultivating fields.

3.3. Optimal rates of N

The estimated coefficients of the fitted production function for the season, soil types and yield outcomes revealed that the soil types have different yield responses to N fertilizer, indicating a difference in inherent soil productivity.

The detailed results are presented in Supplementary Table S11. Statistically significant relationships between the rate of N application and rice yield for the LHG soil in the *Maha* season for all three yield outcomes are shown in Table 3.

Table 2
Estimated coefficients of the nitrate transport functions in LHG soil in the *Maha* season.

Tank name	$NT = A * e^{k*N\ rate}$	
	A	k
Vendarankulama	7.01***	0.0035***
Bulankulama	4.69***	0.0035***
Meegassgama	2.31***	0.0034***
Allisthana	2.43***	0.0038***

*** Statistically significant at 0% of probability level.

3.3.1. The marginal social cost of nitrogen

In estimating the socially optimal N rate, the SCN includes the cost of fertilizer (world market price) and the damage cost of nitrate-N in tank water. The decision framework of Fig. 3 must be amended because the marginal SCN (M_SCN) is not constant for unit increases in N fertilizer since the nitrate transport functions increase exponentially (Fig. 6 and Table 3). The revised framework is in Fig. 7.

3.3.2. Social and private economic N rates

The socially and privately economic optimum N rates (for the framework in Fig. 7 and Table 1) were derived by combining the results from yield response functions and nitrate transport functions. These rates are shown in Table 4 and Supplementary Table S12. As expected, the social optimum N rates were below the optimal private rates in all scenarios. The fertilizer price is a fundamental determinant of the difference between social and private economic N rates. As the fertilizer price reduces under subsidy scenarios, the differences in N rates become larger.

The reductions in N fertilizer rates, rice yields and nitrate transport for the social optimum N rates compared to the optimum private rates are given in Supplementary Tables S13, S14 and S15. Results for the LHG soil type and *Maha* season are in Table 5.

The patterns of changes for the socially optimal N rates compared to the private (subsidized and distorted) N price scenarios in Table 5 show that differences between social and private rates are small when the comparison uses higher (world market) prices for the private fertilizer decisions. At highly subsidized (lower) fertilizer prices, the differences are much larger.

3.3.3. Sensitivity analysis

Results presented in Table 5 were based on 2018 prices. Prices for N fertilizer and rice have increased since 2018. A sensitivity analysis was conducted for the socially optimal N rates with mid-2022 prices for rice, fertilizer and damage costs. The sensitivity analysis scenarios and changed prices are in Table 6. The grain price in 2022 increased three times over the 2018 price, and the fertilizer price increased around eleven times over the 2018 price. The nominal damage cost is more than twice as high as in 2018. The results of the sensitivity analyses are in Table 7 for LHG soil in the Maha season, and the complete set of results is in Supplementary Table S16.

From the price changes in Table 6, we expect that in scenario 1 (as the grain price is increased), the socially optimal N rates will increase from the base. In scenario 2, owing to the much higher relative N fertilizer price, we expect the optimal social N rates to decline from the base. These patterns are generally observed in Table 7 results.

From the decision framework in Fig. 7, we expect that the inclusion of a damage cost for nitrate discharged into tank water will lead to a lower optimal social N rate than the private decisions. These trends are apparent from the results in Table 4 for LHG soil in the *Maha* season. Similar patterns for N fertilizer reductions, yield losses and nitrate transport reduction are shown in Table 5. An important observation

Table 3
Estimated coefficients of the production function in LHG soil in the *Maha* season.

Yield outcome category	$Y = a + b(1 - e^{-kx})$		
	A	b	k
Low	2655.1*	3099.7*	−0.011*
Medium	2954.1*	3238.4*	−0.014*
High	3959.4*	2701.4*	−0.015*

Three simulated yield-outcome categories for growing season weather variability - low (10th percentile of yield), medium (50th percentile of yield) and high (90th percentile of yield).

* Statistically significant at 5% of probability level.

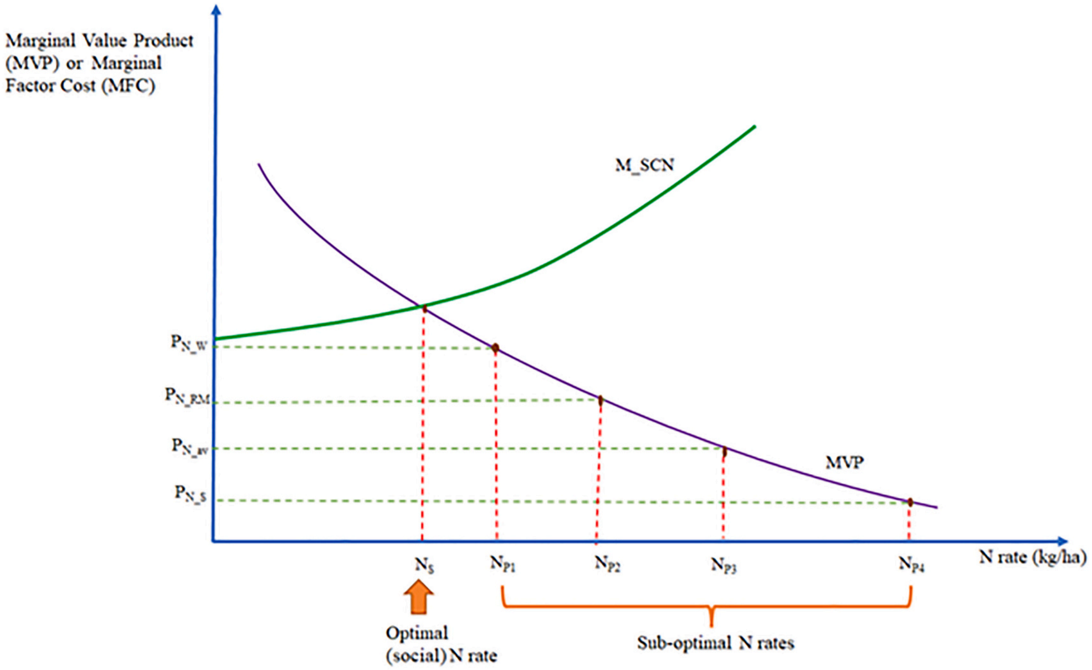

Fig. 7. Decision framework, including the non-linear marginal SCN and alternative N fertilizer prices, includes subsidized price (P_{N_S}), farmer's price(P_{N_AV}), regulated market price (P_{N_RM}), and world market price(P_{N_W}).

Table 4
Estimated optimal (social) and sub-optimal N rates in LHG poorly drained soil in the *Maha* season.

Yield outcome Category	Optimum (social) N rate[a] (kg/ha)	Sub-optimal N rates (kg/ha)			
	N_S	N_{P1}	N_{P2}	N_{P3}	N_{P4}
		At world market price	At regulated market price	At farmers' price	At subsidized price
Low	197	200	230	260	375
Medium	175	177	201	225	315
High	156	158	180	202	287

[a] Nitrate transport functions were tank-soil specific. First, tank-specific social optimal N rates were estimated. Then soil and season-specific social optimal N rates were obtained as weighted averages over tank-soil combinations.

Table 5
Impacts on N fertilizer rates, crop yields and nitrate transport by reaching optimum N rates from sub-optimal N rates, LHG soil and *Maha* season under different N prices.

Soil type	Yield outcome category	N_{P1}	N_{P2}	N_{P3}	N_{P4}
		At world market price	At regulated market price	At farmers' price	At subsidized price
N fertilizer reduction (kg N/ha)	**Low**	3.00	33.00	63.00	178.00
	Medium	2.00	26.00	50.00	140.00
	High	2.00	24.00	46.00	131.00
Yield losses (%)	**Low**	0.21	1.96	3.18	5.34
	Medium	0.13	1.42	2.32	3.90
	High	0.12	1.21	1.99	3.38
Nitrate transport reduction (kg/ha)	**Low**	0.08	0.90	1.81	6.38
	Medium	0.05	0.65	1.30	4.31
	High	0.04	0.55	1.11	3.70

from these results is the impact of fertilizer prices as influenced by public policy. As fertilizer prices are more heavily subsidized, the difference between social and private optimal N rates is accentuated, leading to higher nitrate transport into tanks. The sensitivity analysis results reinforce the importance of fertilizer prices on crop production decisions and associated environmental impacts. The environmental impacts of agricultural practices are the costs that are typically unmeasured and often do not influence farmers or societal choices about production methods when considering only the private benefits of agricultural production (Tilman et al., 2002).

Reducing N fertilizer use is indicated to mitigate the risk of environmental pollution and human health threats in Sri Lanka. This could be accomplished through stringent policies of fertilizer regulation, recommendations for improved N management practices for farmers, training and education of farmers on nutrient management, and public awareness of environmental protection. The N fertiizer-induced negative environmental impact can be mitigated if the socially optimal N rates are adopted, but this depends on the policy of fertilizer subsidization. Weerahewa and Dayananda (2023) also emphasize that a secure market for chemical fertilizers is needed to ensure financially and environmentally sustainable cropping systems. Additionally, the policies related to fertilizer use and policy reforms in rice cultivation need to consider the structure and function of the cascade to ensure resource conservation and sustainable production (Sirimanna et al., 2022).

4. Conclusions

We developed and applied an integrated model to investigate the implications of N fertilizer management on rice crop yields, optimum N fertilizer rates, and nitrate discharges and transportation into nearby water bodies via leaching, runoff and lateral flow. The yield potential varied between soil types, and LHG soil was always the most productive. Soil, seasonal and weather variability cause heterogeneity in indicated optimal social and private N fertilizer rates. Operating at socially optimal N rates was predicted to reduce water quality depletion

Table 6

Scenarios to identify the impacts on optimal N rate by changed grain price, fertilizer price and exchange rate from 2018 to 2022.

Scenario		Grain price (LKR/kg)	Damage cost (2018)[a] (LKR/kg)	N_{p1} (2018) (LKR/kg)	Damage cost (2022)[b] (LKR/kg)	N_{p1} (2022) (LKR/kg)
Base (current result)		40	214	152		
Scenario 1	Increase grain price only	120	214	152		
Scenario 2	Increase grain and fertilizer prices, and damage cost	120			476	1739

[a] The damage cost was converted into Sri Lankan rupees using the exchange rate in 2018. (1 US$ = LKR.161.81)

[b] The damage cost was converted into Sri Lankan rupees using the exchange rate in 2022. (1 US$ = LKR. 360.76).

Table 7

Impacts on optimal N rate by changes in grain price, fertilizer price, damage cost and exchange rate from 2018 to 2022.

Season	Yield outcome Category	Optimum N rate (kg/ha)		
		Base	Scenario 1	Scenario 2
Maha	**Low**	197	175	78
	Medium	175	253	82
	High	156	229	69
Yala	**Low**	128	187	55
	Medium	195	306	53
	High	128	186	54

compared to the private economic N rates when accounting for the effects of nitrate transport into the tank water. The null hypothesis was that fertilizer rates would need to be substantially lowered to reduce nitrate's adverse environmental effects on tank water quality. However, there is very little difference between the social and private optimal N fertilizer rates under unregulated prices. The socially optimal N rates were slightly lower, and the yield differences were quite small. Hence, we reject the null hypothesis when unregulated (world market) prices for N fertilizer were used for comparison. The fertilizer subsidy policy provides private economic benefits to smallholder farmers, yet at the risk of excessive nitrate transport into cascade tanks with consequent effects on water quality for human use if farmers have access to unlimited quantities of fertilizer at a subsidized rate.

This modelling framework can be applied to simulate the effect of alternative fertilizer technologies on crop production decisions, for example, the use of organic N fertilizers and slow-release fertilizers. This model can be applied to evaluate policy questions such as changing the fertilizer subsidy policy and including environmental effects on farmer decisions by other policy mechanisms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103628.

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