Point Source Nitrate Transport Modeling in the Coastal Aquifers

Y. R. Satyaji Rao
Scientist, Deltaic Regional Centre
National Institute of Hydrology,
Kakinada, A. P., India

A. K. Keshari and A. K. Gosain
Professor, Dept., of Civil Engineering
Indian Institute of Technology, Delhi, India

***Abstract* — RISK-N model is presented to analyze quantitatively nitrate transport from faulty septic systems. The model integrates one dimensional unsaturated and two dimensional saturated zone. The estimated percentage ranges of monthly septic system NO_3-N contributions to groundwater by using RISK-N model during July-02 to June-03 at three locations in coastal aquifer are 51 to 65, 61 to 98 and 64 to 90 respectively. The RISK-N model application revealed that the average septic system NO_3-N contribution to groundwater significantly depends up on the prevailing groundwater table conditions and nitrogen load. The sensitivity analysis of model (RISK-N) parameters revealed that vadose zone thickness, seepage from faulty septic-sock pit system, saturated zone denitrification rate and average plot size are the most sensitive parameters.**

Keywords— Groundwater; Septic Tanks; Nitrate; Coastal Aquifers

I. INTRODUCTION

At present, coastal towns or cities in India are facing shortages of freshwater due to groundwater becoming more contaminated in addition to background salinity. Regional snap-shot studies were conducted in the Kakinada coastal aquifer by [1] and [2, 3, 4] for this aquifer. Many researchers reviewed the sources of groundwater nitrate due to non-agricultural activities [5, 6]. Nitrate ion is considered as anthropogenic source indicator of the extent of pollution of urban groundwater from domestic wastes and leaky septic tanks [7]. High nitrates in groundwater affects the human health (especially infants), animals and marine living features [8]. The epidemiological study carried out by [9] on nitrate in drinking water for the Jaipur region, India revealed that there is a significant interdependence among drinking water nitrate concentrations, cytochrome b_5 reductase activity and recurrent stomatitis.

Physically based analytical nitrate transport model ‘RISK-N’ developed by [10] which combines both the unsaturated and saturated zones, with fewer input parameters than any currently available models simulating the complex systems, is used with septic systems. The initial application of this model on corn plots provided reasonable predictions of nitrate leaching to groundwater. The applicability of RISK-N model for urban areas to estimate nitrate leaching to the saturated zone is a first attempt in the field. RISK-N model is tested by [11] in the central valley of Chile on corn plot and carried out sensitivity analysis of the model. The study revealed that the model performs well when spatially averaged values are used and the prediction error increases when the concentration in each well is considered. In the present paper, the estimation of nitrate leaching from septic systems alone is considered to study nitrate transport from leaky septic system in the coastal aquifers.

II. STUDY AREA

Well-known deltas in the East Coast of India are Cauvery, Krishna, Godavari, Mahanadhi and Sundarbans. The Kakinada Municipal Corporation (KMC) and nearby irrigation zone, is a part of the River Godavari eastern delta system in the East Godavari district of Andhra Pradesh, India. The study area between the streams of Eleru and Nakkalakhandi, and has a coast length of about 20 km along the Bay of Bengal (Figure 1). The study area is between 82^0 $10^{'}$ $00^{''}$ to 82^0 $21^{'}$ $41^{''}$ E longitude and 16^0 $55^{'}$ to 17^0 $10^{'}$ N latitude. The main geology of the area is coastal alluvium underlain by Rajahmundry sandstone. Geology of the East Godavari District is also shown in Figure 1. The location of KMC boundary is shown in dashed lines in the Figure 1. The total geographical area of KMC is 30 sq km. The shallow aquifer is under unconfined conditions. The tropical climate is warm from April to June, with a maximum temperature of 40^0 C. The winter months are December and January when the minimum average temperature is 20^0 C. The major portion of rainfall falls during the southwest monsoon from July to September. Annual normal rainfall at Kakinada town is 1095 mm. The average evaporation rate varies from 2.5 to 9 mm/day. The groundwater table varies between 0.5 to 5 m above mean sea level. Nitrogen load estimation from population density in GIS framework in the study area was presented by [12].

III. METHODOLOGY

RISK-N is a physically based analytical nitrate transport model, which links up both unsaturated and saturated zones. The model is capable of simulating both (1) irrigated agriculture and (2) septic tank systems with turf grass. The later is especially important because no physically-based nitrogen cycling models were developed to simulate the combined effect of both septic tanks and fertilized turf grass found in suburban settings. However, in the present paper, the estimation of nitrate leaching from septic systems alone is considered to suit the field conditions. The major processes considered in the RISK-N model for the septic system are shown in Figure 2.

In simulating nitrogen processes, the RISK-N model separates the unsaturated soil into the upper zone, lower zone, drain field zone and intermediate-vadose zone. Transport in each unsaturated soil zone is simulated on the premise of complete mixing of nitrogen concentrations, which is achieved

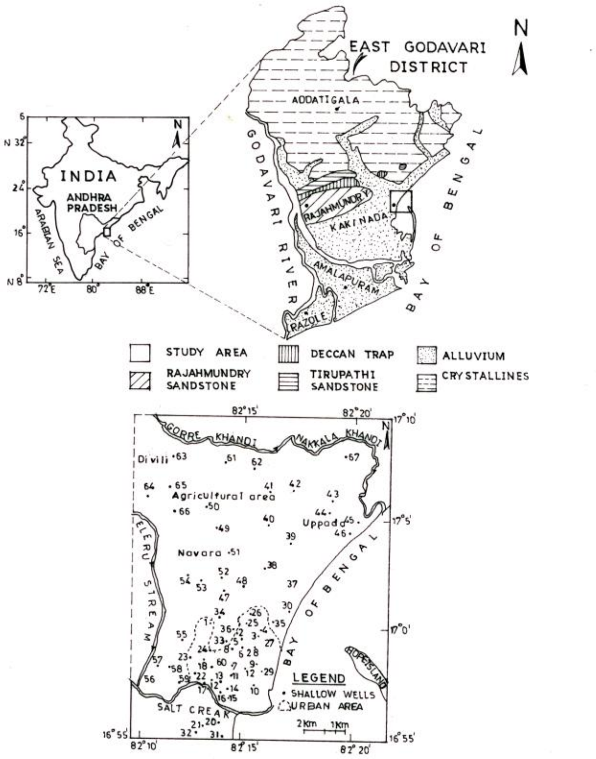

Figure 1. Location of the study area, geology and observation wells

by spatially averaging the nitrogen convective-dispersive partial differential equations. In the saturated zone, this complete mixing assumption is not used. Instead, the two-dimensional convective-dispersive equation is solved analytically. In addition to convection, nitrate in groundwater may be influenced by diffusion, dispersion and denitrification. Rainfall is the main driving variable controlling infiltration, and subsequently leaching of nitrate from the soil. The model allows the use of either (1) seasonal rainfall averages, or (2) rainfall may vary from year-to-year with a stochastic model. The term 'seasonal' refers to the time periods specified by the user for the simulation, from 1 (annual) to 12 (monthly), or any other number in between. A simplified approach for soil water transport is considered in the RISK-N model. All water fluxes are taken as one-directional, steady state, and calculated as monthly averages.

Soil water transport equations

Infiltration into the upper zone can be expressed as (since there is no applied irrigation water in urban environment):

$$q_{ur} = p - r \tag{1}$$

where,
p = precipitation rate (m/year);
r = runoff rate (m/year);

PERCOLATION FROM THE UPPER ZONE IS GIVEN BY:

$$q^*_{ur} = q_{ur} - F_{ur} L_s \quad q^*_{ur} = 0, \text{ if } L_s > q_{ur} \tag{2}$$

where,

L_s = Losses due to septic systems or soak pits (m/year);

$$L_s = K_{septic} * ET_o \tag{3}$$

K_{septic} = septic coefficient for evaporation
ET_o = Class A Pan Evaporation (m)

F_{ur} is the fraction of Evapotranspiration taken from the upper zone. If no crop is grown in a season, then F_{ur} is set equal to one.

Percolation from the lower zone is given by:

$$q^*_{lr} = q^*_{ur} - (1 - F_{ur}) L_s, \quad q^*_{ur} = 0, \text{ if } L_s > q_{ur} \tag{4}$$

Percolation into the drainfield is given by:

$$q^*_d = q^*_{lr} + p_d \tag{5}$$

where,
p_d = the rate of percolation added by the septic drain field (m/yr)

$$p_d = \frac{Flow_{eff} N_{person} F_{house}}{A_{lot}} \left(\frac{365}{10^7} \right) \tag{6}$$

Where,

$Flow_{eff}$ = is the septic tank effluent flow (liter/person/day),

N_{person} = is the number of persons per household,

F_{house} = is the fraction of houses occupied,

A_{lot} = is the average plot size per household (ha), and $365/10^7$ is a unit conversion factor.

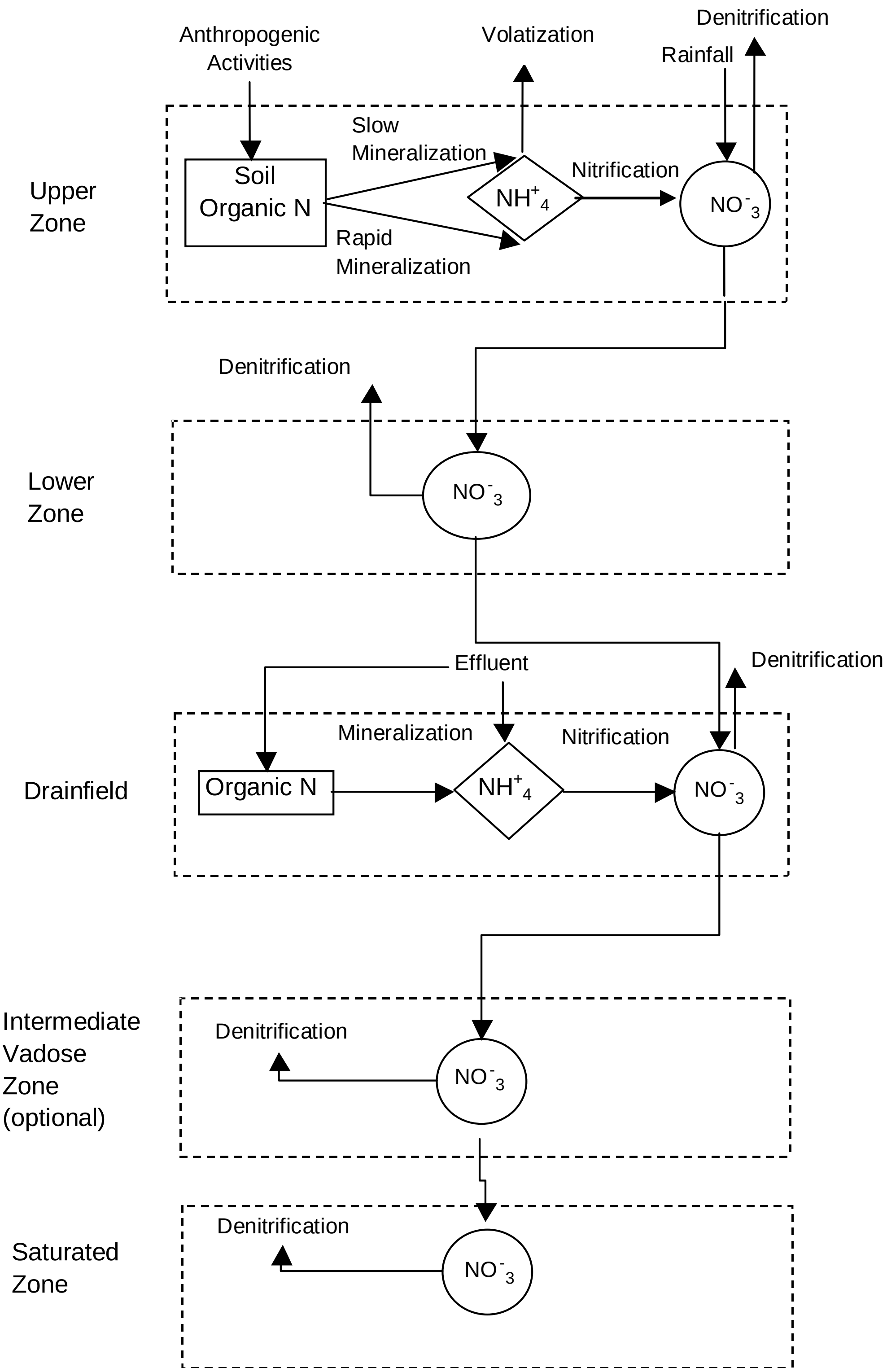

Figure 2 Flow chart showing RISK-N model processes

Pecolation from the intermediate vadose zone is given by:

$q_v^* = q_d^*$ for septic system application (7)

Percolation into the saturated zone is given by

$q_s = q_v^*$ for septic system with intermediate vadose zone (8)

Nitrogen inputs and processes in RISK-N model

A. Soil organic nitrogen

The soil organic N is conceptually divided into active and passive fractions. The active portion includes organic N involved in the process of mineralization, and is divided into rapid and slow mineralization fractions. The rapidly mineralizing N consists of recent additions of manure and crop residue containing organic N. The slow fraction consists of

resident soil N still mineralizing, as well as the remaining organic N from past manure and crop residue applications.

B. Wet and dry deposition

The RISK-N model assumes that the N concentration in rainfall is a constant value of 3 ppm as NH_4^+-N. Local departures from this average value are often found in proximity to ammonia sources such as cattle feedlots, burnyards, and poultry houses. Rainfall near these sources may contain twice the nitrogen concentration as predicted from the regional averages. The 3 ppm default value may be changed when using RISK-N in such areas. The rate of dry deposition defaults to zero in RISK-N, but may also be changed by the user, if desired.

C. Ammonia volatization

The majority of ammonia losses take place during the first 10 hrs to 1 week following fertilizer application, although it may continue over the next several weeks. A constant fraction approach is used in the RISK-N model. For manure, 20% of the urea/ammonium N is assumed to be lost due to volatilization. For mineral fertilizer, this percentage is lowered to 10 %.

D. Mineralization

In its model-calculated rates of mineralization, the RISK-N model does not take into account the effects of the C:N ratio. However, the user has the option of specifying seasonal net mineralization rates. The rate of mineralization varies greatly with soil temperature. In India, mineralization is one of the significant factor, due to high soil temperatures than colder regions. The equations used by the RISK-N model to determine the mineralization rates for the rapid and slow organic N pools are as given below.

The first order rate (day^{-1}) for the rapid fraction is a function of soil temperature, T (^{0}C):

$$k_{mr}(T) = 5.6 * 10^{12} \exp[-9800/(T+273)] F_{wm} \quad (9)$$

while the rate (day^{-1}) for mineralization of the slow fraction is

$$k_{ms}(T) = 4.0 * 10^{9} \exp[-8400/(T+273)] F_{wm} \quad (10)$$

where,

T = Soil temperature;

F_{wm} = water content factor for mineralization and is given by

where,

$$F_{wm} = \theta / f_c \quad if\ \theta > f_c; \quad F_{wm} = f_c / \theta \quad if\ f_c > \theta \quad (11)$$

where,

θ = soil water content (m^3/m^3) and

f_c = water content at field capacity (m^3/m^3)

E. Nitrification

RISK-N uses a first order kinetic to simulate nitrification. The user may supply the nitrification rate constant as input if nitrification inhibitors are used, or else the model uses a default value of k = 1/day.

F. Denitrification

Denitrification rates in the RISK-N model may either be user supplied from the research data or literature or they are calculated by the model using an algorithm described below. When model calculated rates are used, the user has the option to simulate or ignore denitrification in the intermediate vadose zone; denitrification rates are always calculated for the upper, lower and drain field zones, where the organic C is normally available in sufficient quantities. For the saturated zone, the user must specify a rate constant for denitrification, if any; the model does not calculate a value given the high level of uncertainty. The method for determining the denitrification rate coefficients in the unsaturated zones is as follows.

Denitrification rate k_d (k_{dur}, k_{dlr}, k_{dd}, k_{dv} are in upper, lower, drain field and vadose zones respectively) is given by

$$k_d = k_{15} F_{wd} F_t \quad (12)$$

where,

k_{15} = rate coefficient for dentrification at 15^{0}C, equal to 0.01 (day^{-1});

F_{wd} = soil water content (m^3/m^3)

where,

$$F_{wd} = \exp\{0.304 + 2.94(\theta_{sat}^u - \theta^u) - 47(\theta_{sat}^u - \theta^u)^2\}$$

for upper zone (13)

$$F_{wd} = \exp\{0.304 + 2.94(\theta_{sat}^l - \theta^l) - 47(\theta_{sat}^u - \theta^u)^2\}$$

for lower zone (14)

$$F_{wd} = \exp\{0.304 + 2.94(\theta_{sat}^d - \theta^d) - 47(\theta_{sat}^u - \theta^u)^2\}$$

for drain field zone (15)

$$F_{wd} = \exp\{0.304 + 2.94(\theta_{sat}^v - \theta^v) - 47(\theta_{sat}^u - \theta^u)^2\}$$

for vadose zone (16)

where, θ_{sat}^u, θ_{sat}^l, θ_{sat}^d, θ_{sat}^v is the soil water content at saturation in upper, lower, drainfield and vadose zones, respectively (m^3/m^3).

F_t = the temperature factor

where,

$$F_t = 0.67 \exp[0.43(T_{sat} - 10)] \quad if \quad T_{sat} \le 10^0 C$$

and (17)

$$F_t = \exp[0.08(T_{sat} - 15)] \qquad if \qquad T_{sat} > 10^0\, C \qquad (18)$$

where,
T_{sat} =Temperature at saturation (°C).

Governing equations for upper zone (Slow mineralization, rapid mineralization, ammonium mass balance, nitrate mass balance), lower zone (nitrate mass balance), drainfield zone (Ammonia mass balance, nitrate mass balance) and nitrate transport in saturated zone are given by [13].

IV RESULTS AND DISCUSSTION

The location of representative observation wells is shown in Figure 3. The monthly variations of measured groundwater NO_3^--N, rainfall and groundwater levels within the KMC (polygon index 12) are shown in Figures 4 and 5, respectively. The groundwater NO_3^--N concentration in Figure 4 indicates that high population density in Lb nagar shows high concentrations of groundwater NO_3^--N and low population density in Suresh nagar shows low concentrations of groundwater NO_3^--N. The RISK-N model was applied to these three representative locations independently to estimate monthly nitrate-nitrogen contribution from septic systems.

Based on the field conditions, the depth of upper zone, lower zone, drain field zone and intermediate vadose zone are fixed as 0.5, 0.5, 1.0, 0.5 m, respectively, in these three representative areas and the same depths were used in the RISK-N model. However, the saturated zone depths or mixing depths (amsl) at Lb nagar, Suresh nagar and Madav nagar are 3.0, 2.5, and 1.5 m, respectively. The septic effluent total nitrogen concentration is taken as 95 mg/l [14] and the seepage from septic tank/soak pit system per person is taken as 10 l/day (estimated during non monsoon period in the study area). The monthly climatic variables and soil temperatures are kept same for all three representative areas as these areas are close to hydrometeriological observatory. Similarly, the soil properties (porosity, field capacity, bulk density, NH_4^+ adsorption coefficient) are similar at three representative areas as these areas fall in the similar soil type. The monthly

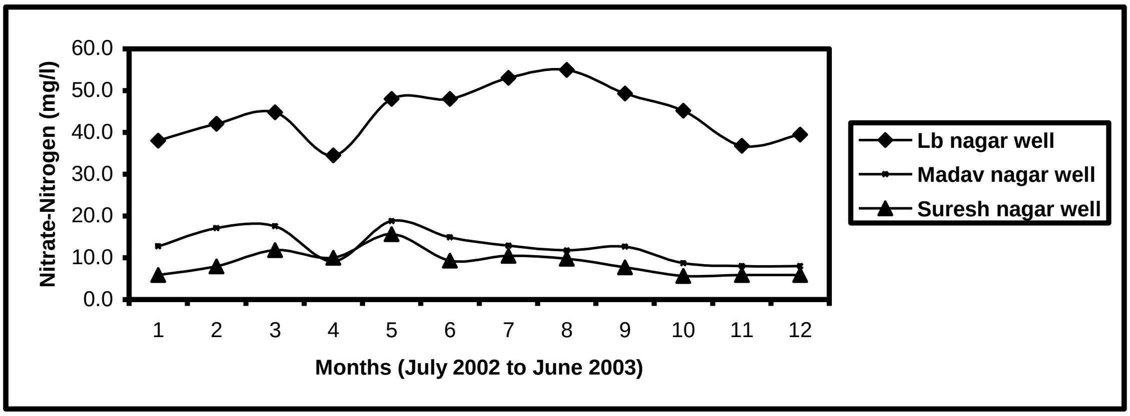

Figure 4. Variation of groundwater **NO_3^--N** (mg/l) concentration

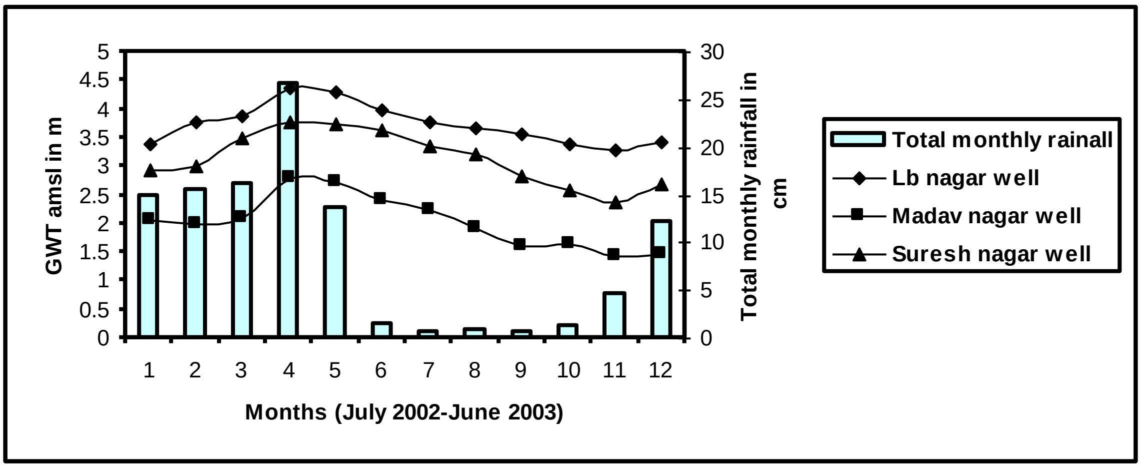

Figure 5. Comparison of rainfall and groundwater table fluctuations

septic coefficient for evaporation (k_{septic}) is taken as 0.15. The monthly average runoff coefficient during June to November is 0.65 (range is 0.48 to 0.89) and December to May is 0.11 (range is 0.07 to 0.19). The monthly water flux in each zone is computed from Equations 1 to 8, and the annual water balances (July 2002 to June 2003) at three representative areas are computed. The average runoff coefficient and the rainfall recharge coefficient obtained from annual water balance are 0.640 and 0.180, respectively. The nitrate-nitrogen flux (gm/m^2) from upper zone, lower zone, drain field zone and intermediate zone were computed for all three well locations. As the major input of nitrogen mass is at the drain field zone, the monthly average nitrate-nitrogen flux (gm/m^2) during July 2002 to June 2003 from the drain field zone and the vadose zone at three representative areas are computed. The average nitrate fluxes from the drain field zone at Lb nagar, Madav nagar and Suresh nagar are 2.09, 0.394 and 0.345 (gm/m^2), respectively. These fluxes are in direct correspondence with the population densities at respective places. Using the flux coming from the intermediate zone and saturated zone properties, the monthly NO_3^--N concentration in the wells were computed by solving 2-D groundwater transport equations. With reference to the mean sea level, the average thickness of the mixing zone or the saturated zone is fixed as + 3.0, +1.5, and +2.5 m at Lb nagar, Madav nagar and Suresh nagar, respectively. The porosity of soil is measured in the field and the average Darcy's velocity is estimated from groundwater gradient and hydraulic conductivity of the soil. The longitudinal and transverse dispersivities of porous medium for nitrate are taken from field-scale dispersion in aquifers. Since the septic system eliminates organic carbon, it is reasonable to assume that denitrification is insignificant below the septic tank. However, in the present study the denitrification rate has been varied between 0.001 and 0.0 to compare the results obtained from the RISK-N model with the measured groundwater nitrate concentrations. The monthly estimated groundwater NO_3^--N concentrations from septic systems using RISK-N model were compared with measured groundwater NO_3^--N concentrations, and the percentage of septic system contribution to groundwater is obtained. The ranges of contribution of septic system nitrate-nitrogen (mg/l) concentration (in percentage) at Lb nagar, Madav nagr and Suresh nagar are 51 to 65, 61 to 98, and 64 to 90, respectively. The average % of septic system nitrate-nitrogen (mg/l) contribution at these three locations is 61, 72 and 71%, respectively. It is observed that the % of septic system NO_3^--N into groundwater mainly depends on the groundwater table condition, the mixing zone depth and the population density. For two different values of denitrification rate (per day) as 0.0 and 0.001 the monthly groundwater NO_3^--N was estimated at three locations by using the RISK-N model and its average values during July 2002-June 2003 are given in Table 1. Results reveal that with zero denitrification rates, the estimated NO_3^--N concentrations are in agreement with average measured groundwater NO_3^--N. Similarly, with the 0.001 denitrification rate the estimated NO_3^--N concentrations are in agreement with minimum measured groundwater NO_3^--N. Since the present study is limited to the extent of nitrate contamination resulting from septic tanks, the results obtained from RISK-N model are not expected to match with maximum nitrate concentrations.

Table 1.Comparison between estimated and measured groundwater nitrate –nitrogen during July 2002 to June 2003

Location	Measured groundwater NO_3^--N (mg/l) during July 2002 to June 2003			Groundwater NO_3^--N (mg/l) obtained from RISK-N model (monthly average)	
	Max.	Min.	Avg.	k_d=0.001	k_d = 0
Lb nagar	55.0	34.0	44.0	22.3	37.0
Madav nagar	19.0	8.0	12.7	8.4	12.0
Suresh nagar	16.0	5.8	8.8	5.7	8.2

V. CONCLUSIONS

The estimated percentage ranges of monthly septic system NO_3^--N contributions to groundwater obtained by using RISK-N model during July 2002 to June 2003 in Lb nagar, Madav nagar, and Suresh nagar areas are 51 to 65, 61 to 98, and 64 to 90, respectively. The RISK-N model application revealed that the average septic system NO_3^--N contribution to groundwater significantly depends up on the prevailing groundwater table conditions and nitrogen load. The sensitivity analysis of RISK-N model parameters reveals that intermediate vadose zone thickness, seepage from septic-soak pit system and saturated zone denitrification rate are the most sensitive parameters. Results obtained from the RISK-N model are valid only when the groundwater table is above the mean sea level.

ACKNOWLEDGMENT

Authors are thankful to Er. R.D.Singh, Director, National Institute of Hydrology, Roorkee for his encouragement to conduct this field study. Technical support extended by Shri. T.Vijaya and Shri. D. Mohan Rangan is duly acknowledged.

REFERENCES

[1] C.K. Jain, Bhatia, K.K.S., and Vijay, T. "Groundwater quality in a coastal region of Andhra Pradesh. Indian". *Journal of Environment and Health*, 1997, 39(3), pp.182-192

[2] Y.R.S.Rao,Vijay, T., Jain, C.K and Seethapathi, P.V. "Groundwater quality monitoring and evaluation in Kakinada coastal aquifer, Andhra Pradesh", *Proceedings of 8th National Symposium on Hydrology* (*Theme: Coastal Hydrology*), 11-12 April 1997, Calcutta, India, pp. 22-26.

[3] Y.R.S.Rao, Vijay, T. and Ramasastri, K.S. "Evaluation of groundwater quality in coastal city-A case study", *Proceedings of 10th National Symposium on Hydrology with Focal Theme on Urban Hydrology*, 18-19 July 2000, New Delhi, India, pp.440-448

[4] Y.R.S.Rao, Keshari, A.K. and Gosain, A.K. "Evaluation of regional groundwater quality using PCA and geostatistics in the urban coastal aquifer, East Coast of India", *Int. J. Environment and Waste Management*, 5, 2000, pp. 163-180.

[5] R.F. Spalding and Exner, M. E. "Occurrence of Nitrate in Groundwater – A review." *Journal of Environmental Quality*, 1993, 22 pp.392-402.

[6] F.T.Wakida and Lerner, D.N. "Non-agricultural sources of groundwater nitrate: a review and case study". *Water Research*, 2005, 39:1, pp. 3-16.

[7] W.G.Reay. " Septic tank impacts on groundwater quality and nearshore sediment nutrient flux". *Ground Water*, 2004, 42(7), pp. 1079-1089.

[8] D.Majumdar and Gupta, N. "Nitrate pollution of groundwater and associated human health disorders". *Indian Journal of Environmental and Health*, 2000, 42(1), pp. 28-39.

[9] S.K.Gupta, Gupta, R.C., Seth, A.K., Gupta, A.B., Bassin, J.K., Gupta, D.K., Sharma, S. "Epidemiological evaluation of recurrent stomatitis, nitrates in drinking water and Cytochrome B Reductase activity." *The American Journal of Gastroenterology.*, 1999, 94(7), pp. 1808-1812.

[10] A.J.Gusman and Marino, M.A. (1999). "Analytical modeling of nitrogen dynamics in soils and groundwater." *Journal of Irrigation and Drainage Engineering*, ASCE, 1999, 125(6), pp. 330-337.

[11] R.Oyarzun, Arumi, J., Salgado, L., Marino, M. "Sensitivity analysis and field-testing of the RISK-N model in the Central Valley of Chile". *Agricultural Water Management*, 2007, 87(3), pp.251-260.

[12] Y.R.S. Rao, Keshari, A.K and Gosain, A.K. "Nitrogen loading from septic tanks in the costal plains". Asian Journal of Water, Environment and Pollution, 2013, Vol.10, No.4, pp.65-76.

[13] Y.R.S.Rao. "GIS linked modeling of Nitrate contamination in the urban coastal aquifer of Eastern Godavari Delta". 2007, Ph.D Thesis, Department of Civil Engineering Indian Institute of Technology, Delhi, New Delhi.

[14] C.H. Rajasekhar, Reddy, V.C., Kotaiah, B. "Groundwater pollution from unsewered sanitation – A case study in Tirupati". *Indian Journal of Environmental Protection*, 1994, 14(11), pp.845-847.