Using GIS for assessing stream water chemistry in a forested watershed

Akiyuki KAWASAKI, Reiji FUJIMAKI, Nobuhiro KANEKO and Satoru SADOHARA

Abstract: Systematic survey preparation and data analysis are required for conducting efficient research on forested mountains because investigating many streams in such an environment is difficult. A methodology of GIS utilization for surveying and analyzing nitrogen leaching in headwaters was demonstrated in this paper. Firstly, support maps for the Tanzawa Mountains, Southern Kanto District, Japan, were created for effective data collection by field surveys. Then, contributions of catchment properties to N-leaching were investigated by spatial analysis using fine-scale terrain data. Finally, N-leaching prediction maps were created for decision-support.

Keywords: forest ecosystem, catchment, water sampling point, nitrogen

1. Introduction
1-1 Background

Nitrogen (N) plays a key role in regulating primary production in ecosystems, especially in land-based systems. Increased human socioeconomic activity has changed nitrogen circulation drastically on a global level. Increased reactive nitrogen from humans through synthetic fertilizers, industrial use, and fossil fuel consumption has been exerting strong influences on the ecosystem. High levels of anthropogenic nitrogen, coming primarily from atmospheric deposition, are recognized as a crucial environmental issue in natural ecosystems on a par with global warming and acid rain (Aber et al., 1998; Galloway et al., 2003). Problems associated with high nitrogen levels were also featured in the United Nations’ Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005). A major symptom caused by increased nitrogen input to forested catchments is increased nitrate (NO$_3^-$) concentrations in stream waters, which can cause eutrophication and acidification in freshwater and coastal waters, which deteriorates water quality while threatening human health (Vitousek et al., 1997).

There is an increasing need to understand stream water quality. In general, researching streams in an entire watershed is difficult due to its large area. Therefore, systematic monitoring location planning and analysis are crucial for effective research. Recent developments in information technology such as Geographic Information Systems (GIS) allow the rapid arrangement of a spatial data infrastructure and comprehensive analyses of various kinds of spatial data. Consequently, GIS offer promising tools for planning and analyzing the study of stream water quality in large-scale forested watersheds. This paper provides a case study on applying GIS to streamwater research in the Tanzawa Mountains of northwestern Kanagawa Prefecture, central Japan. The Tanzawa Mountains are an important area because most
Kanagawa Prefecture residents depend on the area as a source of water. For that reason, deterioration of water quality in this area is a critical issue for Kanagawa water resources. This area, located in Japan’s southern Kanto district, is most likely affected by anthropogenic disturbances. Okochi and Igawa (2001) reported high nitrate concentrations in a stream in the Tanzawa Mountains, but their study was limited to only one stream; so water chemistry patterns on a broader scale within the Tanzawa Mountains remains unclear. Additionally, nitrogen leaching from forest ecosystems varies significantly because of many factors like differences in geology (Willard et al., 2005), hydrology (Shibata et al., 2001), watershed topography (Creed and Band, 1998), and tree species composition (Lovett et al., 2000).

1-2 Objective

The research team for this study consists of geologists, pedologists, and vegetation scientists. The team has been trying to explain nitrogen leaching mechanisms from forest ecosystems and proposed a future strategy of forest management (Kaneko and Fujimaki, 2006; Sakai et al., 2007). The research project involved conducting a general field survey to assess the current nitrogen leaching from forest ecosystems in the Tanzawa Mountains. The study described in this paper specifically examines the utilization of GIS for survey and analysis. This paper proposes and describes implementation of spatial information utilization for promoting efficient nitrogen leaching assessments in forested mountain headwaters.

GIS have been used to investigate the characteristics of watersheds for many purposes; for example, Luzio et al. (2004) developed a model to assess agricultural non-point and point pollution loading at the watershed scale; Downs and Priestnall (1999) studied river channel adjustments; and Kaur et al. (2004) analyzed the impact of land-use planning on soil conservation by using a watershed-scale hydrologic model. Specifically as a preceding study, Jarvie et al. (2002) investigated the relationship between river chemistry and watershed characteristics, including landuse, topography and geology, using GIS and statistical analysis for the Humber catchment in England. In addition, nitrogen leaching factors at the catchment scale in forested mountains in Japan were analyzed using a 50 meter mesh digital elevation model (DEM) (Ito et al., 2004; Ogawa et al., 2006). However the priority and process of selecting water sampling points remain unclear, and spatial patterns of nitrogen loss in streams and the cause of the pattern were analyzed within the watershed delineated from these sampling points. A methodology for designing sampling points are necessary to consider forest management in the Tanzawa Mountains, which consists of precipitous terrain combined with a variety of geology and vegetation over a broad area.

In this study, survey supporting maps were prepared for effective data collection in the field by considering some working hypotheses. Then, factors contributing to water chemistry were analyzed using fine-scale spatial data in an individual catchment. Finally a “nitrogen leaching prediction map” was created for decision support concerning the type and location of actions to properly manage future forest ecosystems in the Tanzawa Mountains.

Fig. 1 Research site
2. Developing working hypotheses and allocating sampling points

2-1 Study area

The Tanzawa Mountains are located in the northwestern part of Kanagawa Prefecture, in an area extending 50 km east and west and 30 km north and south. The mountain range is located where the Philippine, Eurasian and North American continental plates collide, and it was formed by the collision of the Honshu Arc and the Izu Arc. Japan’s highest rates of orogenic uplift and denudation by the Izu-Arc are still observed here (Arima and Kaneko, 2006) and the topography is composed of steep slopes. The impact of atmospheric pollution is apparent in the Tanzawa Mountains. The distance from the center of the Tokyo metropolitan area, where Japan’s socio-economical activities are concentrated, is approximately 50 km. In the mountains, 11.3 kg-N/ha/year of nitrogen deposition was measured in Ooyama and 13.3 kg-N/ha/year was measured in Fudagake (Asou et al., 2001).

Six river systems in the mountains were studied (Fig. 1): the Hayato River and Shimizu River flowing to Miyagase Lake in the eastern part; and the Kurokura River, Nakagawa River, Oomatazawa River, and Yozuku River flowing to Tanzawa Lake in the western part. The Tanzawa region straddles both Kanagawa and Yamanashi Prefectures, but only the Kanagawa side was chosen due to personnel limitations. The total research area was 21,000 ha: 95.7% of the area was covered by forest, 2.5% by waste land, and 1.6% by water (National-Land Information Office, 1997). The elevation of the area ranges from 290 to 1,673 m with an average of 851 m.

2-2 Preparing datasets and characterizing catchments

To assess the influences of topography, geology and vegetation on water quality, headwater outlets discharged from various small catchments were targeted as sampling points. The tentative size of the catchments was limited to less than 80 ha so that the results could be applied to a selection of future experimental sites for long term monitoring. For example, the Hubbard Brook Ecosystem Study for a US site of the Long Term Ecological Research (LTER), on ecosystem patterns and processes in a watershed, selected nine watersheds of less than 80 ha for observation (Hubbard Brook LTER, 2008). Further consideration of the catchment size is required if this unit is suitable for complex topography in Japan, or for considering topography, geology, vegetation and soil as a unit, and how heterogeneous characteristics inside the catchment is changed as the catchment size increases.

Several GIS datasets were collected and analyzed to find appropriate sampling points (Table 1). First, as an interpolation-conversion from elevation point to raster dataset, catchments were delineated using a DEM with a 12 m cell size using ESRI ArcGIS Desktop 9.1 and Spatial Analysis. The DEM was generated from vector elevation data called GISMAP Terrain. Although the nominal resolution of the data is 10 m, we produced the 12 m DEM due to the

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parameter setting of the interpolation-conversion module of the software. The Tanzawa Natural Environment Information Station by Kanagawa Prefecture also adopted a 12 m cell size for deriving a DEM from the same data (Kanagawa Prefecture Natural Environment Conservation Center, 2006).

With a flow accumulation grid delineated from the DEM, streams were defined through a flow accumulation value of 1,500 cells. A threshold flow accumulation of 1,500 cells with a 12 m cell size correspond to a drainage area of 216,000 m² or 21.6 ha. The reasons for defining a threshold value and verification of water flow status are described in section 3-2. Next, stream junctions were treated as catchment outlets. As a result, 139 headwater-catchment sampling points were selected from the study area.

The watershed characteristics of the selected sampling points were classified according to the following properties (Fig. 2).

**Elevation:** Catchments were categorized into two elevation groups: one with mean elevation greater than 800 m, the other less than 800 m. At this latitude (35°24' – 35°37'N), native vegetation growing at elevations higher than 800 m is different from that growing in lower areas. Cool-temperate natural mixed forests with deciduous broadleaf trees (beech) and conifers (fir and hemlock) prevail in upper elevations, whereas temperate evergreen broadleaf forests prevail in the lower areas (oak). Nowadays, the latter areas are dominated by secondary vegetation and conifer plantations such as cedar and Japanese cypress (Sakai, 2006). These changes in vegetation type, along with elevation, might alter the nitrogen retention in catchment areas.

**Slope:** Slope gradient was assumed to influence water transfer speeds on the surface and inside the soil, as well as to affect soil depth. Mean slope gradient was used to categorize catchments into three types: <30°, 30–35°, and >35°, since thick loamy volcanic soils tend to cover moderate slopes less than 30°, and granitic tonalite soils cover a broad range of slopes but the soil depth tends to decline inversely with the gradient in the Tanzawa Mountains (Kaneko et al., 2007; Sakai et al., 2007). Granitic tonalite soils have higher productive capacity of nitrates per organic substance than volcanic ash soils, because organic matter in granitic tonalite soils tends to have higher mineral content. Slopes around 30° and higher were considered to have high nitrate production rates because such slopes are mainly covered by granitic tonalite soils.

**Geology:** The eastern part of the research site is covered by tuff bedrock developed in the Miocene...
(Tertiary) period, and the western part on the other side is mainly covered by plutonic bedrock (granitic tonalite). This geological distribution was assumed to have a significant influence on stream water chemistry and ecosystem material flow by affecting vegetation and chemical weathering of the soil. Furthermore, such mechanisms might influence the buffering capacity against nitrogen deposition in forest water systems.

**Vegetation:** The catchments are dominated by degraded trees due to a lack of forest management, and this may strongly influence nitrate leaching. Consequently, the catchments were categorized as “natural forest, plantation forest or mixed vegetation” by calculating the dominant vegetation (>70% of the area) of each catchment. Catchments were categorized as having mixed vegetation when either natural or plantation forest covered less than 70% of the total area. The value of 70% was a tentative threshold.

### 3. Implementation of water sampling

#### 3-1 Survey outline

A general survey by six teams with 25 members was conducted to assess nitrogen leaching in the Tanzawa Mountains headwaters on July 13th and 14th, 2006. Each team was supplied with two types of the river system map highlighting sampling points and catchment properties (Figures 3 and 4), 1:25,000 Geographical Survey Institute (GSI) topographical maps, longitude and latitude of sampling points, and GPS units. Some members were familiar with the study site, while some were not. Team members were assigned to collect samples from watersheds that have various characteristics of elevation, slope, geology and vegetation in a balanced manner using survey support maps.

Despite initially aiming to acquire 100 samples out of 139 candidate points in Fig. 2, the survey ultimately yielded 51 samples of water, soil and leaves (bamboo grass and Polygonum cuspidatum), including several unplanned points due to topographic difficulty in accessing several planned points, time restrictions, and heavy rainfall on July 14th (Figures 5 and 6). The points not surveyed were either too far from main road, too dangerous for data collection (rough landscape and swollenness of stream), or unsuitable in terms of the balance of the watershed characteristics. For supporting a more systematic survey, focusing on priority areas by preliminarily considering catchment properties and displaying optimal routes might be useful. Achieving over half of the intended water samples in this short period under imperfect conditions was considered successful.

Additionally, the GPS units including Trimble
Pathfinder Pro XR and ProXH provided accurate location information (accuracy of less than 1 m using real time differential correction), which allowed the effective surveying and collection of sample points. However, GPS signals were often insufficient due to the forested mountainous terrain, so the GSI topographical maps were used to supplement the searching tasks.

3-2 Verifying the status of headwater flow extracted from the DEM

No standard processes exist regarding what methodologies and parameters to use for extracting streams using a DEM, and it is possible to delineate a wide range of stream features using GIS depending on the data used, analysis resolution, extraction parameters and methodologies, etc (Kawasaki, 2006; Maidment, 2002). In this study, sampling points were designed from catchments and stream data delineated from the DEM, as described in section 2-2. In general, water chemistry analysis gets more complicated with larger catchment areas, and it is ideal to collect samples from the upper reaches of a catchment to assess the effects of topographical features, geology, and vegetation on water chemistry. Therefore, it was necessary to capture accurate locations of headwaters not described even in the GSI topographical map. For that reason, headwaters that regularly maintain at least a minimum level of flow despite seasonal and conditional variability had to be extracted using GIS.

Accordingly, a flow accumulation value of 1,500 cells was defined as the stream delineation threshold based on the knowledge of experts familiar with a part of the study area (Nishizawa catchment, 306 ha). The experts compared various kinds of stream data extracted using a range of thresholds, and determined the most suitable threshold to describe actual water flow including small streams.

During the survey, stream flow at the planned points was verified including locations at which actual water samplings were not implemented. Inventory forms were distributed to each team and the status of water flow was identified as one of the four categories in Table 2 by visual observation. The table shows that actual water flow in various statuses was verified at most locations checked during the survey. Total rainfall was recorded as 2 mm for one week prior to the survey (July 7th - 13th), and 94 mm for the past two weeks (June 30th - July 13th) at the neighboring Tanzawa Lake observation site (Japan Meteorological Agency, 2006). The results shown in Table 2 might be biased since the results were limited to only those locations accessed, and some field survey members might have selected easier locations for obtaining water.

4. Analysis and modeling of nitrogen leaching

4-1 Chemical analysis and mapping the result

Stream water, soil, and leaf samples were used to assess water chemistry such as pH balance, water temperature, nitrate (NO$_3^-$), NH$_4^+$, total nitrogen (TN), and dissolved organic carbon (DOC). The result was outlined in this paper and utilized to create the nitrogen leaching prediction map in section 4-2.

The mean concentration of TN of all stream water was 0.74 mg-N/L, ranging 0.18 mg/L to 1.30 mg/L with over 95% containing nitrate (Figures 5 and 6). The factors shown in Fig. 2 were almost equally distributed because of the use of the survey support maps (Figures 3 and 4). Nitrate concentrations in headwaters of the eastern Tanzawa Mountains tend to be higher than those of western areas (Fig. 6), which corresponds to differences in geology: the eastern part consists of tuff bedrock, whereas the western part consists of plutonic bedrock (Fig. 2). Chemical analysis methods and equipments, as well as the results and mechanisms of Nitrogen leaching in the Tanzawa Mountains are described in Fujimaki.
et al. (2008)

4-2 Predicting model of nitrogen leaching

A general linear model was used to predict the nitrogen concentrations in streams using topographic characteristics in the catchment areas. The following parameters were assessed.

a) Distance from the Yokohama city center (km)
b) Distance from the Sagami Bay coast line (km)
c) Total catchment area (ha)
d) Mean catchment elevation (m)
e) Catchment elevation standard deviation (m)
f) Catchment elevation range (maximum − minimum, m)
g) Catchment mean slope (deg.)
h) Catchment slope gradient standard deviation (deg.)
i) Proportion of steep slopes (>30°) area to total catchment area (%)
j) Most frequently observed slope aspect category
k) Mean of the cosine-transformed value of the slope aspect azimuth: The cosine of the slope aspect azimuth represents the degree of north facing, ranging from -1 to 1.

l) Mean catchment Laplacian value
m) Standard deviation of catchment Laplacian value

From the geological map and the vegetation inventory, each catchment was categorized as follows:

n) Most frequently observed bedrock geology in three categories (plutonic, tuff, and volcanic tuff)
o) Dominant vegetation (>70% of area) in three categories (natural forest, conifer plantation, and mixed vegetation);

Model selection was performed according to Akaike’s information criterion (AIC), a statistical reference for determining the suitability of statistical models among several options (Venables and Ripley, 1999). Lower AIC values indicate a better model based on the lowest squares of residual sum but with a penalty for the greater number of parameters. The software program R 2.6.0 (R Development Core Team, 2007) was used for the statistical analysis. The selected model was;

\[ TN = 2.5913 - 0.2389k - 0.1541h - 0.0071a, \]

where \( TN \) is total nitrogen concentration (mg-N/L) in stream waters, \( k \) is mean of the cosine-transformed value of the slope aspect azimuth, \( h \) is catchment slope gradient standard deviation (deg.), and \( a \) is distance from Yokohama city center (km) \( (R^2 = 0.343, AIC = -5.19, F = 8.17, p < 0.001). \)

\( TN \) was negatively related to \( k \), showing that stream \( TN \) tends to be high when the proportion of south-facing slopes increases. This is because soils
in south-facing slopes tend to be warmer, probably promoting nitrogen mineralization and nitrification. TN was also negatively correlated to \( h \), indicating that nitrogen is less likely to leach with more complex terrain, but this exact mechanism requires further investigation. Additionally, the Tanzawa Mountains, directly facing the Kanto Plane where Yokohama is located and where industry and agriculture are highly developed, receive reduced nitrogen loads that are inversely proportional to \( a \). Additional interpretation of individual parameters is described in Fujimaki et al. (2008). AIC analysis also yielded the following model:

\[
TN = 2.1577 - 0.1954k - 0.1473h
\]

\( (R^2 = 0.313, AIC = 4.91, F = 10.91, p < 0.001) \).

This second model had fewer parameters than the first model with little difference in AIC value, although the coefficient of determination was less. Fig. 7 shows the results of the first model fitted to a topographical map. Continuing surveys and analyses with additional consideration are required for improving the scientific credibility of this study because this map was extrapolated from spatial nitrogen leaching patterns observed on July 13th to 14th, 2006. This map, however, can contribute to effective and advanced surveys in the future by illustrating where to collect water in an efficient manner.

5. Conclusions

This study used GIS for supporting sampling point selection to analyze nitrogen leaching in headwaters and explained the available methodologies. The following results were obtained:

1. Survey support maps were created to locate sampling points and field data collection. Headwaters in small catchments with different properties were successfully extracted.

2. Spatial analysis based on fine-scale terrain data was used to investigate the effects of catchment topography like slope gradient and slope aspect on nitrogen leaching.

3. A nitrogen leaching prediction map was created for the entire Tanzawa Mountains based on data from 51 sampling points. Estimation of the status of the broad range of mountains and considering further desirable countermeasures are possible, by expanding the analysis results in small catchments to the broad range of all mountains using GIS, where capturing aerial ecosystem data was difficult.

Further debate is required on how to use GIS for creating a material flow model to predict nitrogen status in mountain headwaters and estimating effective countermeasures using scenario analysis.

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References


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