Evaluation of Water Conflict Using Hydrological Model and GIS

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論文内容要旨

In recent years, water supply shortage has become an urgent issue in Southeast Asia. Water demand is increasing with the rapid economic development and urbanization. On the other hand, surface water supplies are being menaced by land use change. In the northern Thailand, the prevalent views are that logging, shifting cultivation by mountain ethnic minorities, and commercial agriculture in highland watersheds, that cause severe dry-season water supply shortages. Water demand is the other side of the equation, as it also places constraints on water availability. Dynamics of water use relate to land use change, especially through expansion of lowland cultivation, irrigated upland fields, urban areas, and industrialization

This study conducts a quantitative water resources assessment of the Mae Chaem River Basin, Northern Thailand (Fig.1), an area that confronts problems such as dry season water scarcity and water use conflicts between upstream and downstream inhabitants. The Mae Chaem River Basin was divided into 21 sub-basins for evaluation.

The block-wise TOPMODEL with the Muskingum-Cunge flow routing method (BTOPMC) was used to predict runoff in sub-basins. The model was calibrated with water discharge at 3 stations based on the index of agreement (IA). Simulations were carried out for 1989 and 2000 and IA being between 0.83 and 0.92. The geographic information system (GIS) was employed to collect necessary information for crop water demand evaluation. GIS techniques were also applied to produce erosion hazard indices or erosion estimates using Revised Universal Soil loss Equation (RUSLE). Results of BTOPMC, which were used to compare the available water supply and crop water demand, indicated that the available data in the basin are sufficient to address the water conflict problems.

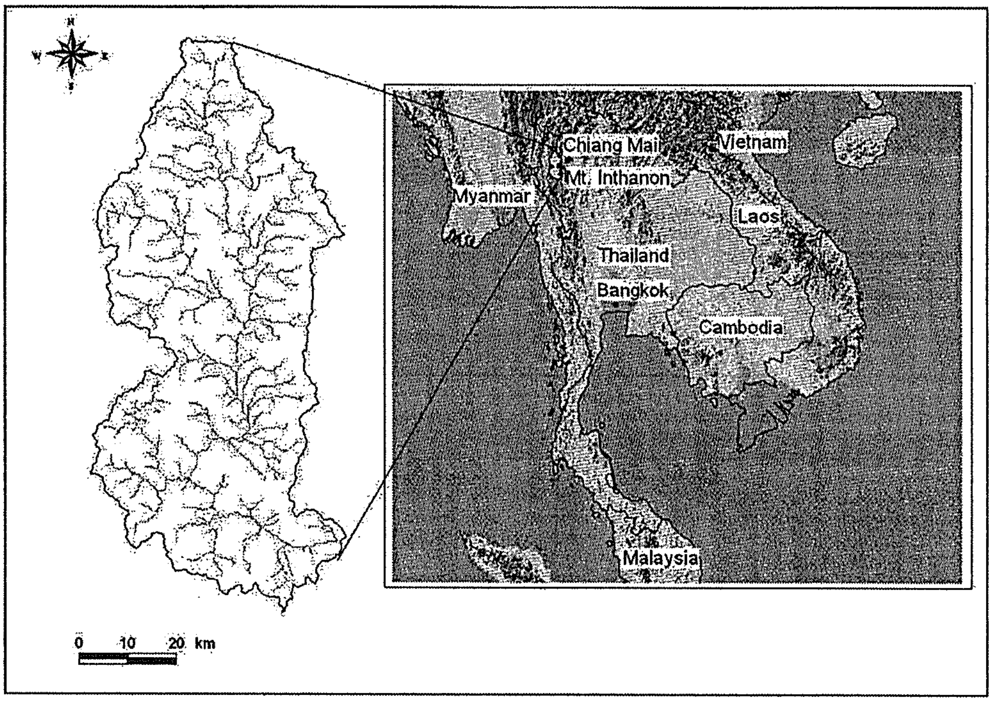

Figure 1. Location of the Mae Chaem River Bain

Water deficits were addressed using two indicators: the water sufficiency index (WSI) for the dry season and the upstream contribution index (UPI) for the wet season. To assess the water sufficiency in a specific sub-basin i (i=1,..n), an index was developed based on the ratio of the difference of streamflow (available water) and crop water demand (RO-WD) to the available water (RO). The water sufficiency index was defined as

$$WSI_i = \frac{RO_i - WD_i}{RO_i} \tag{1}$$

where RO is the streamflow at the outlet of sub-basin i (m^3) and WD is the water demand of sub-basin i (m^3).

This WSI, which was calculated on monthly basis, was used as an indicator of the degree of water sufficiency at the basin level. Negative WSI values denote water shortage in corresponding sub-basin.

When an upstream area has a water deficit, it adversely affects the downstream water supply. Upstream inhabitants draw large amounts of water from the stream, which engenders a reduction of downstream flow when upstream areas have a water deficit. That reduction of downstream water creates problems for downstream inhabitants. This situation worsens if the downstream area also has a water deficit. Therefore, we defined a condition called the combined water sufficiency index (CWSI), to reflect the interaction between upstream and downstream areas. CWSI is defined in a matrix form.

$$CWSI = (WSI_{up}, WSI_{down}) \tag{2}$$

If CWSI has a both minus value of WSI_{up} and WSI_{down} (-, -), (area C of Figure 2), it indicates that both upstream and downstream areas have deficits, thereby creating water conflicts in both upstream and downstream areas. Consequently, there is no water deficit either upstream or downstream, if CWSI has both plus value of WSI_{up} and WSI_{down} (+, +), (area B of Figure 2). Figure 2 and Figure 3 show the CWSI for each node in January 1990 and January 2001. It portrays the occurrence of water conflicts in sub-basins 9 and 10 in 2001, because water deficits exist in both upstream and downstream areas. This situation had not occurred in January 1990. Figure 2 shows a fair situation between upstream and downstream in January 1990 because WSI value in upstream was almost equal in the WSI value in downstream and all CWSI points located in area B. According to Figure 3, sub-basins with both positive WSI (area B) show no water conflicts and a fair situation in both upstream and downstream. If these nodes were moved to area C (-, -) or area D (+, -) the future water demand and supply might be vulnerable. Long-term evaluation using long-term data is highly recommended for that kind of estimation. Nodes in area A of Figure 3 [e.g., (5, 7), (10, 15), (18, 20), (19, 20)] show that upstream areas have a water deficit, but downstream areas display no water deficit in January 2001. This situation is not likely to create water conflict between upstream and downstream areas, but in these nodes, upstream sub-basins use a larger amount of water than available water, which is apparent in sub-basins 5, 10, 18, and 19.

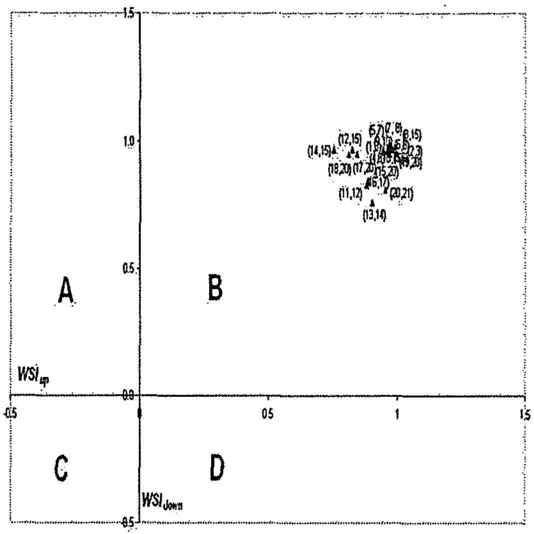

Figure 2. CWSI in January 1990

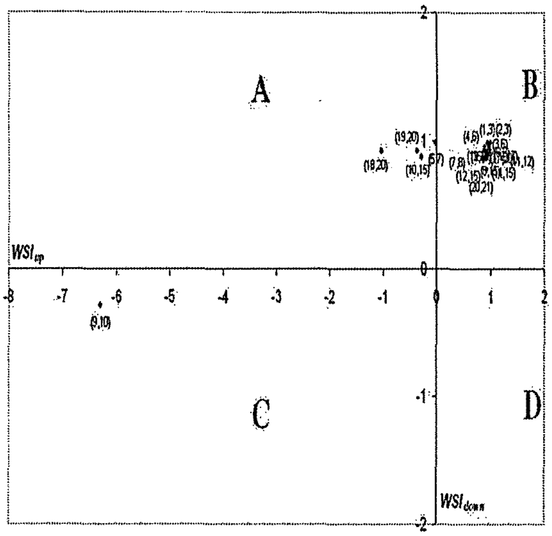

Figure 3. CWSI in January 2001

Furthermore, the water conflict in the wet season was discussed taking disastrous flooding into account. Downstream inhabitants have complained that flooding occurs because of deforestation in the upper watershed. Therefore, we computed the peak discharge per unit area, $(\frac{Q_{peak}}{A})$, for each sub-basin. The catchment area is the most suitable factor to relate hydrology to the difference of this ratio upstream and downstream. It facilitates the assessment of the upstream contribution index (UCI), as shown by Equation 3:

$$UCI = \left(\frac{Q_{peak2}}{A_2} \right) - \left(\frac{Q_{peak1}}{A_1} \right) \qquad (3)$$

where Q_{peak1} is the peak discharge at downstream, A_1 is the area contributes to the discharge at downstream point, Q_{peak2} is the peak discharge at upstream and A_2 is the area contributes to the discharge at upstream point.

In addition, Different Soil Erosion Degree (DSED) was introduced based on the soil erosion classification. Results of RUSLE have been categorized on the five classes; (1) non-erosion, (2) slight erosion, (3) moderate erosion, (4) severe erosion and (5) very severe erosion. The classification of soil erosion degree was made by Land Development Department (LDD). The high value of DSED shows some sub-basin has much more serious soil erosion level. It will increase sediment in the basin and reduce river channel capacity.

$$DSED = \%SVS_{2000} - \%SVS_{1989} \qquad (4)$$

where $\%SVS_{2000}$ is converge ratio of soil erosion able area (from severe to very severe class) in whole sub-basin in 2000 and $\%SVS_{1989}$ is converge ratio of soil erosion able area (from severe to very severe class) in whole sub-basin in 1989.

Soil erosion upstream contribution index (*SEUCI*) asses the potential to occur downstream flood due to sediment deposition in downstream beds. SEUCI can be shown as in Equation 5:

$$SEUCI = DSED_2 - DSED_1 \qquad (5)$$

where $DSED_1$ is Different Soil Erosion Degree at downstream and $DSED_2$ is Different Soil Erosion Degree at upstream. A high value of SEUCI indicates the possible increase of upstream soil eroded to downstream areas.

In this study, we used water inequality method to estimate distributions of water resources (e.g. water availability and potential water resources). Lorenz curves are used to determine the water inequality to estimate distribution of water resources. We compared the Gini coefficients of the Mae Chaem River Basin versus Gini coefficients for whole Thailand to understand the water inequality in small-scale basins and large areas.

Both indicators showed that sub-basin 9 (Upper Mae Suk watershed) faces the worst situation, with water deficits during both dry and wet seasons. Even though there is no overall critical water conflict exists in the basin, sub-basins 9, 10, 12, and 15 show critical water conflicts in 2000. Moreover, the present situation is much worse than that of the last decade because of land use change. This study shows that deforestation resulting from conversion of forestlands into agricultural lands has engendered water scarcity in the dry season, flooding in the wet season and soil erosion. Deforestation in upstream mountain areas engenders a higher peak discharge, which results in downstream flooding. With increasing demands for improved upstream watershed management, a pressing need exists to implement sustainable land use strategies, which would serve the respective interests of upstream and downstream communities. Utilization of GIS as an analytical tool, confirmed that such modern tools are effective for investigating practical problems and for detecting important features of water resources.

論文審査結果の要旨

気候変動に伴う渇水や降雨パターンの変化，人口増加に伴う水需要の増加によって水紛争が顕在化している．水紛争は，地域から国際問題まで様々なスケールで生じる．タイ国北部マエチャム川流域では，新たに開墾された山岳地域の住民と下流の住民の間で紛争が生じている．この問題を例として，定量的な水紛争評価手法の提案を行うと同時に，水紛争の問題を考察したものが本論文である．論文は全８章よりなる．

第１章は序論である．

第２章は既往研究について様々な水文モデル，土砂流出モデルの性質と開発史について記述している．

第３章は研究対象領域と利用データについて述べている．タイ国北部のマエチャム川流域の状況と，数値計算に利用するデジタルデータの特徴，ソースについて説明している．また，GIS による人工衛星のデータ解析手法についても説明している．

第４章では，マエチャム川流域において，土砂侵食式（USLE）を適用し，流域の土砂生産分布を推定した．この結果を人工衛星画像により分類した森林伐採地域，植林地域において解析し，土砂災害と森林の関係について考察した．その結果，土砂生産と森林の減少の間に明確な相関関係があり，これを定量的に評価することが可能になった．流域全体では植林の効果が大きく，土砂災害は減少の傾向にある．こうした特性を定量的に示したことは新しい知見である．

第５章では，水文モデルと土地利用データを用いて水資源量の分布を調べた．水文モデルは分布型物理モデルである BTOP-MC モデルを構築し，降雨-流出過程を精度よく再現した．また，耕作域の水需要量と水資源量を比較した結果，水資源が雨季には過剰となり，乾季には不足となる地域が定量的に把握された．熱帯モンスーンの山岳域の灌漑用水の需給についての考察は稀有であり，貴重な解析結果である．

第６章は，５章の計算結果を用いて，水紛争を乾季と雨季の時期に分けて評価する指標の提案を行った．乾季には水充足指数の提案を行い，現地調査で得られた対立地域とよい一致が見られた．また雨季には上流貢献度指数の提案を行い，下流の洪水地帯の住民がもつ感情とよい相関を得ることができた．乾季と雨季の水紛争を客観指数で表現することは今まで行われておらず，水紛争解決のための重要な研究成果であるといえる．

第７章は水利用の不公平性について，ジニ係数を用いてマエチャム川流域内の地域とタイ国各流域を比較した．その結果，マエチャム川の各地域は，タイ国内の流域に比べると公平性が高く，水紛争には地政学の視点も必要なことが示唆された．ジニ係数を水資源評価に用いたのは，世界に先駆けてのことであり，数値モデルの利用により可能になった．本手法の発展性は大いに期待できる．

第８章は結論である．

以上要するに本論文は，数値モデルを利用し，水充足指数と上流貢献度指数を提案し，水紛争を定量的に評価することに成功した．また，数値モデルとジニ係数を併用して水利用の不公平さを議論した．本研究成果は，水紛争の定量的な解析，水資源マネジメントに大きく貢献できるものである．
よって，本論文は博士（工学）の学位論文として合格と認める．