タイ王国

経済社会開発局
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天然資源・環境省　水資源局

タイ王国
チャオプラヤ川流域
洪水対策プロジェクト

最終報告書

追加報告書：RRI モデルによる チャオプラヤ川洪水解析

平成 25 年 9 月
(2013 年)

独立行政法人
国際協力機構（JICA）

株式会社建設技研インターナショナル
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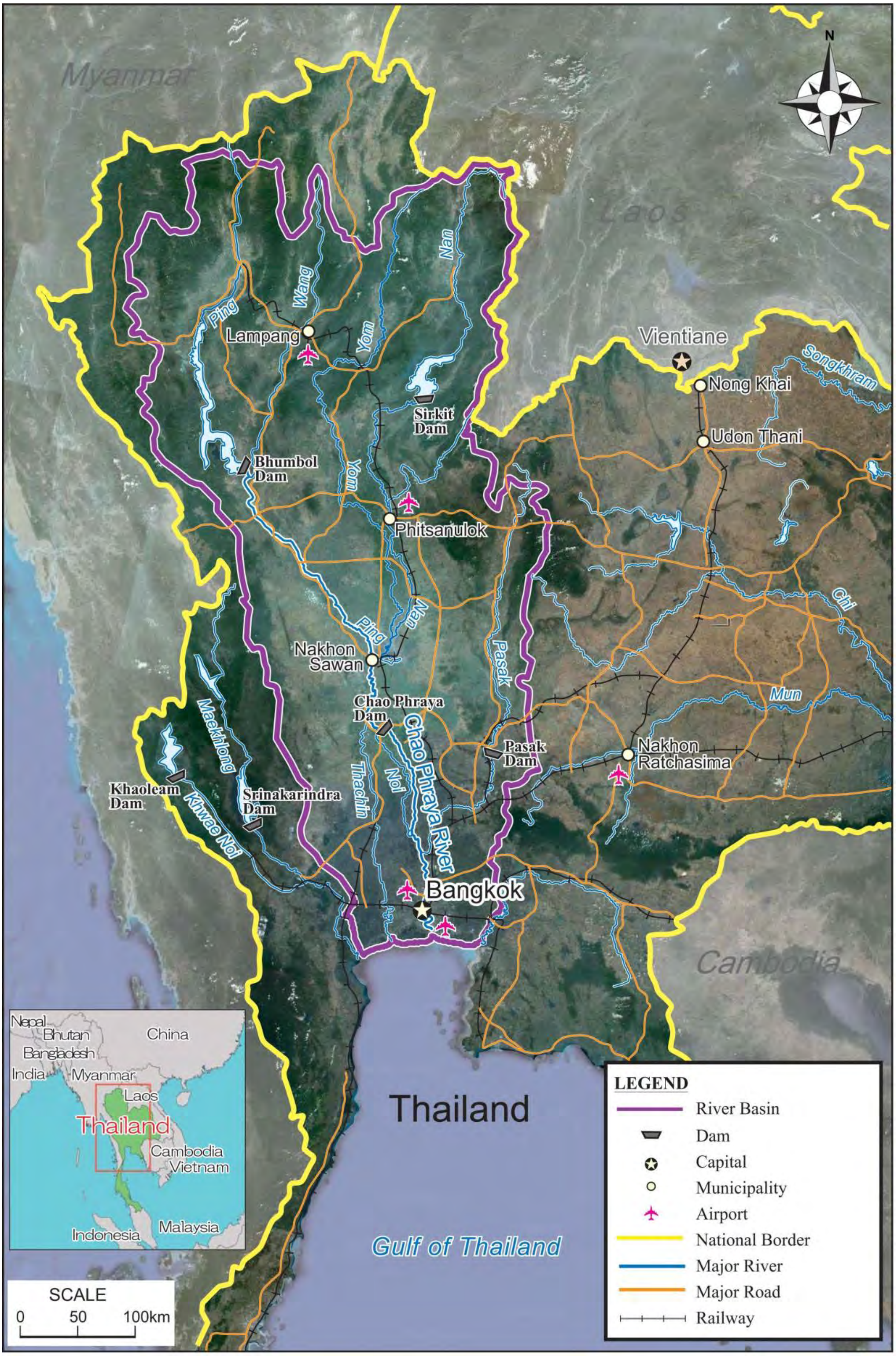
報告書構成

第１巻　　　　　要　約

第２巻　　　　主報告書

追加報告書　　**RRI** モデルによるチャオプラヤ川洪水解析


Myanmar
Laos
Vientiane
Nong Khai
Udon Thani
Songkhram
Lampang
Ping
Wang
Yom
Nan
Sirkit Dam
Bhumbol Dam
Phitsanulok
Chi
Nakhon Sawan
Pasak
Mun
Chao Phraya Dam
Chao Phraya River
Pasak Dam
Nakhon Ratchasima
Maeklong
Khaoleam Dam
Srinakarindra Dam
Khwae Noi
Thachin
Noi
Bangkok
Cambodia
Thailand
Gulf of Thailand
Nepal
Bhutan
China
Bangladesh
India
Myanmar
Laos
Thailand
Cambodia
Vietnam
Indonesia
Malaysia
SCALE
0 50 100km
N
LEGEND
River Basin
Dam
Capital
Municipality
Airport
National Border
Major River
Major Road
Railway

<u>流　域　図</u>

タイ王国
チャオプラヤ川流域洪水対策プロジェクト

最終報告書
追加報告書: RRIモデルによるチャオプラヤ川洪水解析

流　域　図
略　語　集
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略 語 集

AIT	Asian Institute of Technology（アジア工科大学）
ALRO	Agricultural Land Reform Office（農地改革局）
BMA	Bangkok Metropolitan Administration（バンコク都）
CAT	Communication Authority of Thailand（タイ通信公社）
CPB	The Crown Property Bureau（王室財産局）
DDPM	Department of Disaster Prevention and Mitigation（災害防止軽減局）
DDS	Department of Drainage and Sewerage, BMA（バンコク都排水下水局）
DEDP	Department of Energy Development and Promotion（エネルギー開発及び推進部）
DF	Department of Fisheries（水産局）
DGR	Department of Groundwater Resources（地下水局）
DIW	Department of Industrial Works（工場局）
DOH	Department of Highway（高速道路局）
DOLA	Department of Local Administration（地方行政局）
DOR	Department of Rural Road（地方道路局）
DPT	Department of Public Works and Town and Country Panning（公共事業都市計画局）
DPW	Department of Technical and Economic Cooperation（技術経済協力局）
DTCP	Department of Town and Country Planning（都市計画局）
DWR	Department of Water Resources（水資源局）
EGAT	Electricity Generating Authority of Thailand（タイ発電公社）
FFC	Flood Forecasting Center（洪水予報センター）
GISTDA	Geo-Informatics and Space Technology Development Agency（地理情報・宇宙技術開発機関）
GOT	Government of the Kingdom of Thailand（タイ王国政府）
ICHARM	International Center for Water Hazard and Risk Management（水災害・リスクマネジメント国際センター）
IEC	Irrigation Engineering Center（灌漑技術センター）
IMPAC-T	Integrated Study Project on Hydro-meteorological Prediction and Adaptation to Climate Change in Thailand（気候変動に対する水分野の適応策立案・実施支援システムの構築プロジェクト）
JETRO	Japan External Trade Organization（日本貿易振興機構）
LAO	Local Authority Organizations（地方自治体）
MD	Marine Department（海洋部）
MI	Ministry of Industry（工業省）
MOAC	Ministry of Agriculture and Cooperative（農業協同組合省）
MOI	Ministry of Interior（内務省）
MNRE	Ministry of Natural Resources and Environment（天然資源環境省）
MOSTE	Ministry of Science, Technology and Environment（科学技術環境省）
MOT	Ministry of Transport（運輸省）
MST	Ministry of Science and Technology（科学技術省）
NDPMC	National Disaster Prevention and Mitigation Committee（防災委員会）
NESDB	National Economic and Social Development Board（経済社会開発局）
NEB	National Environmental Board（環境委員会）
NWRFPC	National Water Resources and Flood Policy Committee（水資源洪水政策委員会）
NWRC	National Water Resources Committee（水資源委員会）
NSO	National Statistic Office（統計局）

OBI	Office of the Board of Investment（投資委員会）
OCS	Office of the Council of the State（自治委員会）
OEPP	Office of Environmental Policy and Planning（環境政策計画事務局）
ONWRFPC	Office of National Water Resources and Flood Policy Committee （水資源洪水政策委員会事務局）
OPM	Office of the Prime Minister（首相官邸）
OSCWRM	Office of Strategic Committee for Water Resources Management （水資源管理戦略委員会事務局）
PAT	Port Authority of Thailand（港湾局）
PCD	Pollution Control Department（公害管理局）
RBC	River Basin Committee（河川流域委員会）
RFD	Royal Forest Department（王室森林局）
RID	Royal Irrigation Department（王室灌漑局）
RTN	Royal Thai Navy（タイ王国海軍）
RTSD	Royal Thai Survey Department（タイ王国測量局）
SCRFD	Strategic Committee for Reconstruction and Future Development （再建及び将来開発戦略委員会）
SCWRM	Strategic Formulation Committee for Water Resources Management （水資源管理戦略委員会）
SRT	State Railways of Thailand（タイ国有鉄道）
THB	Thai Baht（タイバーツ）
TMD	Thai Meteorological Department（タイ気象局）
TOT	Telecommunication Organization of Thailand（タイ電話公社）
WRFMC	Water Resources and Flood Management Committee（水資源洪水管理委員会）

単　位

(Length)

mm	:	millimeter(s)
cm	:	centimeter(s)
m	:	meter(s)
km	:	kilometer(s)

(Area)

mm^2	:	square millimeter(s)
cm^2	:	square centimeter(s)
m^2	:	square meter(s)
km^2	:	square kilometer(s)
ha	:	hectare(s)

(Weight)

g, gr	:	gram(s)
kg	:	kilogram(s)
ton	:	ton(s)

(Time)

s, sec	:	second(s)
min	:	minute(s)
h, hr	:	hour(s)
d, dy	:	day(s)
y, yr	:	year(s)

(Volume)

cm^3	:	cubic centimeter(s)
m^3	:	cubic meter(s)
l, ltr	:	liter(s)
MCM	:	million cubic meter(s)

(Speed/Velocity)

cm/s	:	centimeter per second
m/s	:	meter per second
km/h	:	kilometer per hour

第1章 RRIモデルを用いた洪水対策M/Pの検証

1.1 はじめに

タイ王国チャオプラヤ川流域洪水対策プロジェクトにおいて、水資源管理戦略委員会（Strategic Committee for Water Resources Management　以下、SCWRM）が作成した水資源管理 M/P に基づき、科学的・技術的分析を踏まえ、チャオプラヤ川流域洪水対策案を提案した。

本調査の水理解析は、デンマーク水理・環境研究所（DHI、http://www.dhisoftware.jp/）の MIKE シリーズを用いて行った。MIKE シリーズは、流出解析や河道追跡計算、氾濫解析、地下水の解析、水質など、様々な水理・水文解析に適用可能なソフトウェアである。このため、世界中の研究機関や開発援助プロジェクトにおいて利用されている。

MIKE シリーズは、ユーザー・フレンドリーで優れたインターフェイスを装備し、使用実績も多く、信頼性の高い水理解析ソフトウェアであるが、ソフトの価格が高額であることや、ソースコードが公開されていないため解析エンジンの実態が明らかでないこと、パラメータの設定箇所が多く、精度の高いモデルを構築するためには、高度な水理・水文学の知識が必要であることなど、途上国のエンジニアが使いこなせるソフトとは言い難い側面がある。

本調査では、早急な治水対策を求めるタイ国政府のニーズに応えるための予備検討として、2012 年の 4 月に、（独）土木研究所 水災害・リスクマネジメント国際センター（ICHARM、http://www.icharm.pwri.go.jp/index_j.html）が開発した RRI モデル（Rainfall-Runoff-Inundation Model）を用いて、2011 年洪水の再現計算が行われた。RRI モデルは河道追跡計算と氾濫解析が可能な分布型流出計算モデルであり、流域を表現するための DEM データ（標高）と河川の流下方向の 2 つの情報を最低でも準備すれば、流出・氾濫解析モデルの構築が可能である。RRI モデルは、計算時間が比較的短く、洪水流量（ハイドログラフ）の再現性が高いことから、コンポーネント 3「洪水情報システムの改善と洪水予測システムの開発」[1]で導入した洪水予測システムの解析エンジンとしても用いられている。

ここでは、追加検討として、RRI モデルを用いた洪水対策 M/P の検証計算を行った。RRI モデルの実用性を検証し、今後の RRI モデル開発における課題を整理する。なお、本調査では、RRI モデルは洪水予測システムに導入されている version1.3 に断面特性を読み込む機能が追加された version1.4β を使用する。

[1] 本調査は、3 つのコンポーネントで構成される。コンポーネント 1 は、新しい詳細地形図の作成と「洪水管理計画」の更新、コンポーネント 2 は、緊急修復事業（水門の設置及び国道 9 号線の嵩上げ）、コンポーネント 3 は洪水情報システムの改善と洪水予報システムの開発である。

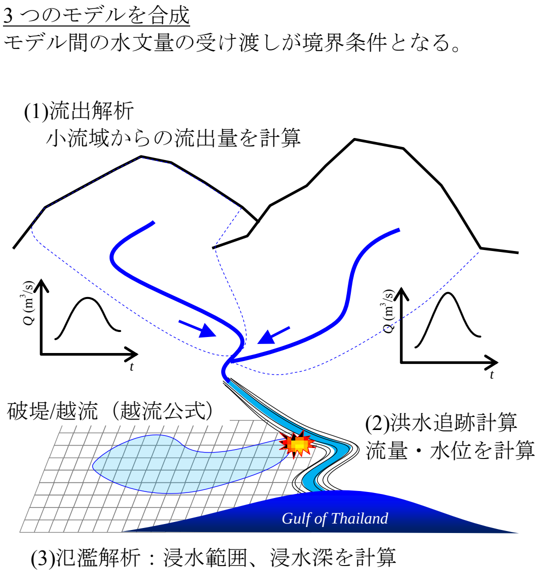
1.2　RRIモデルとMIKEシリーズの比較

前述したとおり、RRI モデルは ICHARM が開発した水理解析モデルである。モデルの概要については次章で整理する。表 1.2.1 に MIKE シリーズと RRI モデルの比較を示す。

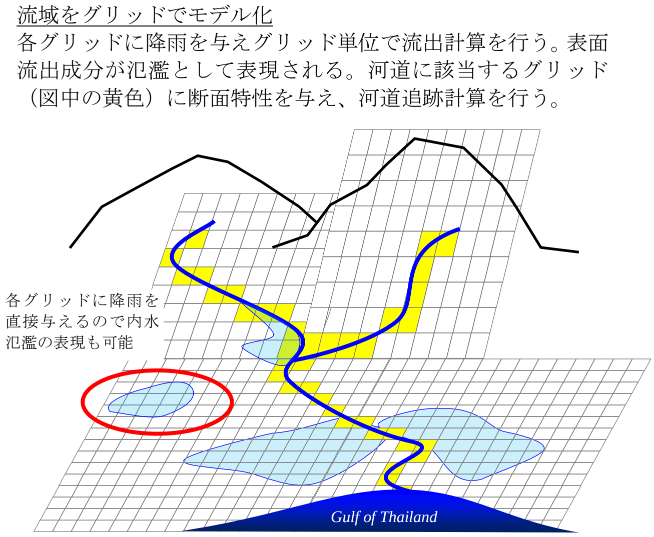
MIKE シリーズと RRI モデルの大きな違いはモデルの構造である。MIKE シリーズで氾濫解析を行う場合は、次の 3 つの解析モデルを個別に構築し、モデルをカップリング（MIKE-FLOOD を使用）することで、降雨から氾濫までの水理現象を表現する。このモデルの構造は、国土交通省の直轄河川で現在用いられている氾濫解析手法と同じである。

(1) 流出解析モデル（MIKE-11 RR モジュール）
(2) 河道追跡計算モデル（MIKE-11 HD モジュール）
(3) 氾濫解析モデル（MIIKE21）

RRI モデルは、分布型流出計算モデルに河道追跡計算と氾濫計算の機能が付加されたモデルであり、構築するモデルは一つである。表面流出や窪地における貯留/湛水、地下への浸透など、流出機構を忠実にモデル化でき、内水氾濫も同時に解析することができる。洪水追跡については各計算グリッドに断面特性を与えることで計算する。断面特性の入力数がグリッドサイズに依存するため（各グリッドに 1 つの断面特性を入力）、河道追跡計算については MIKE-11 やアメリカ工兵隊の HEC-RAS といった河道解析ソフトに比べて精度は若干劣るものの、外水氾濫と内水氾濫を同時に解析できる点は、自然遊水効果の大きい大河川流域の氾濫解析に有利である。なお、MIKE シリーズでは、氾濫解析モデル（MIKE21）の計算グリッドに降雨高を与えることで内水氾濫を表現することは可能であるが、あらかじめ内水氾濫区域を指定する必要がある。



【MIKE シリーズを用いた洪水解析】



【RRI モデルを用いた洪水解析】

株式会社建設技研インターナショナル
株式会社オリエンタルコンサルタンツ
日本工営株式会社
株式会社建設技術研究所

表 1.2.1　RRI モデルと MIKE シリーズの機能比較

2013 年 8 月上旬時点

項目	RRI モデル	MIKE-シリーズ
1.流出計算		
モデルタイプ	グリッド型モデル（分布型モデル） 流域を DEM 等の標高グリッドデータで表現。各グリッドの流出量を求める。各グリッドで計算された流出量は、水位勾配に従って、表面流出や中間流出となり、河川へ流出する。	集中型モデル 流量を求めたい地点で流域を分割する。各流域からの流出量は、境界条件として河道追跡モデルに与える。
計算手法	Diffusion Wave モデル （Kinematic Wave モデルの選択も可能）	NAM（タンクモデルの一種） UHM（単位図法）等の選択可能
蒸発量	グリッド毎に設定可能	流域毎に設定可能
浸透流	グリッド毎に設定可能 Green-Ampt モデル（鉛直浸透）とダルシー則を用いた側方浸透の計算が可能。 浸透流はヘッド差に応じて 8 方向 (4 方向の選択も可能）に移動可能。	流域毎に設定可能 （流域間の地中流の移動は計算不可）
その他	流出計算と氾濫解析は同時に行われる。 流域境界を別途設定する必要はない。	NAM モデルは中・長期流出の再現性が比較的良い（その他、NAM モデルでは融雪洪水の取り扱いも可能）。 内水氾濫については、平面二次元計算の計算グリッドに降雨高を与えることが可能。ただし、あらかじめ内水氾濫区域を設定する必要がある。
2.河道追跡計算		
水理モデル	一次元モデル Diffusion Wave モデル （Kinematic Wave モデルの選択可）	一次元モデル Full-Dynamic モデル （Diffusive モデル、Kinematic モデルの選択可）
河道データ	測量断面および矩形断面 測量断面データから河道断面特性（H-S-B-N　水位、潤辺、水面幅、粗度係数）を作成し、河道に該当する計算グリッドに与える。矩形の場合は河道の幅と深さのデータを与える。 河道断面特性は、各計算グリッドの中央部で 1 断面分の情報を与える。	任意断面 横断測量データの値をモデルに与える。 断面特性は自動計算される。
河道粗度	任意 断面特性データに入力する。水深に応じた合成粗度係数を与えることで、高水敷と低水路の粗度係数を考慮可能。	任意 河道断面に任意の範囲で設定可能（例、高水敷と低水路）。
分派・合流計算	分派は、ユーザーが任意で分派率/分派流量を与えることで表現。合流は計算可能。	ネットワーク状の河道追跡計算が可能。 河道形状や本川・支川の水理条件をもとに、自然分派や合流における水理量の算出が可能。
河川構造物	N/A	堰や水門やカルバート等、構造物のモデル化が可能。その他に、橋梁による水位上昇等の計算が可能。

項目	RRI モデル	MIKE-シリーズ
越流（河道⇔堤内地）	本間の越流公式 左右岸で個別に越流の有無を評価することはできない。ただし堤内地盤高を調整することで左右岸別の越流を表現することは可能。	本間の越流公式（その他に複数の越流公式を選択可能） 左右岸別の越流量の算定が可能。
破堤	任意の地点で破堤のモデル化が可能。破堤時刻の設定可能。 左右岸で個別に破堤の有無を評価することはできない。ただし堤内地盤高を調整することで左右岸別の越流を表現することは可能。	N/A
3.平面二次元モデル（氾濫解析モデル）		
水理モデル	Diffusion Wave モデル （Kinematic Wave モデルの選択も可能）	Full-Dynamic モデル
グリッド（解像度）	任意	任意
座標系	直行座標系	直行座標系
地形データ	DEM でモデル化	DEM でモデル化
堤内地粗度係数	各グリッドに任意で設定	各グリッドに任意で設定
堤内地構造物	連続盛土は、標高データ（DEM）を調整することで表現可能。	連続盛土は、標高データ（DEM）を調整することで表現可能。 フラックス制御によるモデル化も可能（例えば、あるグリッドの水位は 50cm 湛水するまで隣接するグリッドへ越流しないといった制御が可能）。
蒸発量	考慮可	考慮可
浸透流	考慮可 流出計算の浸透流を参照	N/A 浸透流を単独で設定できない。蒸発量の数値に上乗せすることで、浸透を考慮する。
内水排除の検討	検討可能 水路については、河道モデルとして考慮可能。ただし、排水ポンプのモデル化ができないため、排除する水量を蒸発量として設定し考慮する。	検討可能 内水区域に水路ネットワークを構築し、その水路と河川の接続部にポンプをモデル化する。
その他		風による水位の吹き上げの計算も可能
4.その他		
境界条件	ダム放流量や潮位データを境界条件として与えることが可能。	河道モデル、平面モデルともに任意の地点に流量および水位を与えることが可能。
ビューアー	一般財団法人河川情報センター（FRICS、http://www.river.or.jp/index.html）が Graphical User Interface（GUI）を開発（2013 年 8 月）	MIKE View、MIKE-ZERO 河川の水位や流量、氾濫原の氾濫水深や流速等の可視化が可能。

項目	RRI モデル	MIKE-シリーズ
ソース コード	Fortran90/95 により記述 研究開発者向けにプログラムコードの公開を検討中（2013 年 9 月時点） 公開された場合、ユーザーによるモディファイが可能	不明 プログラムコードは非公開
販売/供給元	水災害・リスクマネジメント国際センター（ICHARM） http://www.icharm.pwri.go.jp/index_j.html	DHI Water & Environment 社 （デンマーク水理・環境研究所） http://www.dhigroup.com/
動作環境	Windows7（64bit 版）上での作動を確認	Windows7（64bit 版）上での作動を確認
価格	検討中	河道モデル（MIKE11）や平面モデル（MIKE21）、洪水解析モデル（MIKE-FLOOD）、解析結果の Viewer（MIKE-View）など必要なモジュールおよび計算ノード数を無制限とした場合、約 400 万円（1€≒130　JPY 2013 年 9 月）
備考		・ArcGIS（ESRI 社、US）との親和性が高い。 ・タイ国に代理店有（DHI Thailand）
その他	モデルの入力データは、境界条件等（潮位やダム放流量など　一次元データ）を除き、二次元配列データで整理されている。このため GIS ソフトが使えればモデルの設定は簡単。	・モデルの設定箇所が多く、モデル構築は煩雑。扱いには慣れが必要。 ・DHI 独自の計算処理が組み込まれており誤った入力に対しても計算してしまう。このため計算結果の精査が不可欠であり、水文/水理の知識が必要。

表 1.2.2　　チャオプラヤ川の洪水解析における設定条件の比較

項目	RRI モデル	MIKE-シリーズ
1.流出計算		
計算手法	Diffusion Wave モデル	NAM モデル
蒸発量	グリッド毎に設定	流域毎に設定
浸透流	グリッド毎に設定	流域毎に設定
内水氾濫	通常の計算において内水氾濫を考慮するため、特に設定する必要はない。	チャオプラヤダム下流の内水氾濫域（地形勾配がフラットな区域）については、直接降雨高を与える。
2.河道追跡計算		
水理モデル	一次元 Diffusion Wave モデル	一次元 Full-Dynamic モデル
河道データ	断面特性を考慮して設定。	2005-2006 年測量断面をベースに二線堤の断面（LiDAR から作成）を補完
河道粗度	河川毎に設定可。合成粗度係数　0.023～0.100	河川毎に設定。0.023~0.045（低水路）、0.070~0.100（高水敷）
分派・合流計算	2011 年の観測流量をベースに分派率および分派量を設定。	自動的に計算される。
河川 構造物	N/A	チャオプラヤダム等主要な横断構造物をモデル化
越流（河道⇔堤内地）	本間の越流公式を使用。	本間の越流公式を使用。
破堤	破堤箇所を 10 地点設定。	破堤箇所に水門や越流堰等をモデル化し、疑似的に破堤現象を表現する。

項目	RRI モデル	MIKE-シリーズ
3.平面二次元モデル（氾濫解析モデル）		
水理モデル	Diffusion Wave モデル	Full-Dynamic モデル
グリッド（解像度）	60 秒（約 1,800m）	2,000m
座標系	直行座標系 緯度経度でグリッド位置を指定	直行座標系 UTM 座標系でグリッド位置を指定（WGS84_Zone47N）
地形データ	LiDAR のデータをベースとし、LiDAR の測量範囲外は SRTM で補完	LiDAR のデータをベースとし、LiDAR の測量範囲外は SRTM で補完
堤内地 粗度係数	流域毎に設定。0.060～0.500	2010 年の土地利用に応じて設定。土木研究所のマニュアル（H8 年）の標準的な粗度係数を用いて加重平均で設定。2011 年の洪水氾濫の拡大を再現できるよう補正。0.050～0.600
堤内地 構造物	主要な道路をモデル化（LiDAR）	主要な道路をモデル化（LiDAR）
蒸発量	全流域、一律　4mm/日で設定	TMD の観測データを使用。ティーセン分割により各グリッドに日蒸発量を時系列で設定
浸透流	ナコンサワン下流域で Green-Ampt モデルによる鉛直浸透を、上流についてはダルシー則による側方浸透を考慮	試算の結果、地下浸透として 10mm/日を設定
内水排除	主要な水路は河道モデルとして考慮。ポンプ（蒸発量としてカウント）は未設定。	主要水路およびポンプをモデル化。
その他		風による水位の吹き上げの計算も可能
4.その他		
境界条件	ブミポンダムやシリキットダム、パサックダムの下流に放流量を与える。チャオプラヤ川およびタチン川の河口には潮位データを設定。	ダム下流地点や流域の最上流地点に流量ハイドロを設定。残留域については、河道沿いにハイドロを等分して設定。チャオプラヤ川とタチン川に潮位データを設定。

第2章 RRIモデルの概要

本章では RRI モデルの概要について述べる。なお以下の説明は、「降雨流出氾濫解析テキスト作成業務報告書：平成 23 年 3 月　独立行政法人土木研究所」を引用している。

2.1　RRIモデルの概要と特徴

降雨流出氾濫モデル(Rainfall-Runoff-Inundation Model: RRI Model) は、降雨を入力として河川流出から洪水氾濫までを一体的に解析するモデルである（図 2.1.1）。

降雨流出と氾濫とを２次元で一体的に解析することによって、従来の分布型流出モデルでは再現の難しかった低平地における流出氾濫現象の再現が期待できる。また、谷底平野を有する山地域においては、広域を対象にしてどの地域で浸水の危険性があり、その浸水深がどの程度になるかを推定することができる。

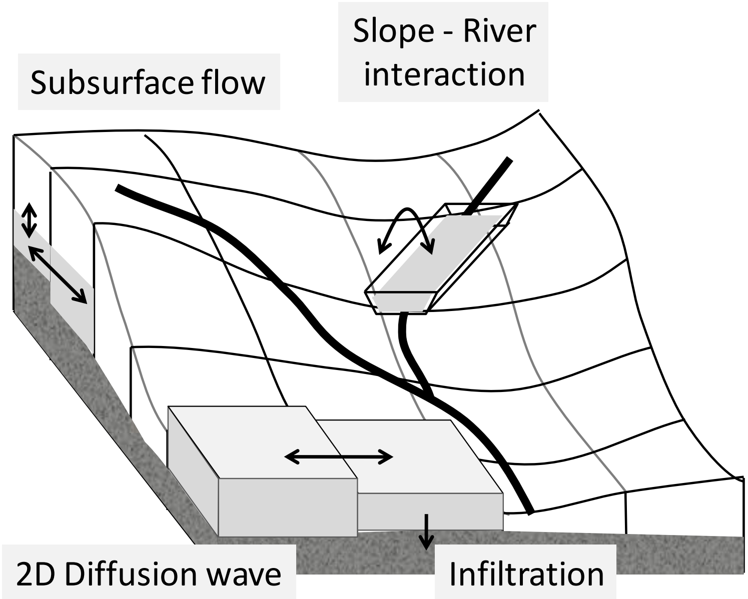


図 2.1.1　降雨流出氾濫モデル（RRI Model）の概要

【降雨流出氾濫モデルの特徴】

1) 拡散波近似した運動量方程式を二次元に展開し、流出と氾濫とを一体的に解析する。
2) 降雨流出過程をより妥当に表現するため、地中部の降雨流出過程（鉛直浸透流および側方地中流）を考慮する。
3) 斜面部と河道部とを分け取り扱い、河道部にも１次元の拡散波近似モデルを適用する。また、斜面部と河道部との水のやり取りを越流公式で計算する。

2.2 RRIモデルの支配方程式

RRI Model の斜面部には、２次元の浅水方程式を拡散波近似した式を用いる。拡散波近似を仮定することにより、浅水方程式を直接解放する場合に比べて、計算負荷を小さくすることができる。また、数値解法には５次の適応時間ステップルンゲクッタ法を採用することにより、数値誤差に応じて適宜時間ステップを調整しながら安定的に解析を進める。

【斜面部の２次元浅水方程式】

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r \quad \cdots \quad (1)$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial u q_x}{\partial x}+\frac{\partial v q_x}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{gn^2 u\sqrt{u^2+v^2}}{h^{1/3}} \quad \cdots \quad (2)$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial u q_y}{\partial x}+\frac{\partial v q_y}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{gn^2 v\sqrt{u^2+v^2}}{h^{1/3}} \quad \cdots \quad (3)$$

ここに、h は水深、u, v は x, y 方向の流速、q_x, q_y は x, y 方向の流量フラックス($q_x=uh$, $q_y=vh$)である。また、r は降雨強度、g は重力加速度、t は時間、H は基準面からの水位である。n はマニングの粗度係数である。

【斜面部の 2 次元拡散波近似式】

RRI モデルが仮定する拡散波近似は、（２）、（３）式の慣性項(左辺の項)を十分に小さいものとして無視する。さらに、x 方向と y 方向とを分けることによって、つまり、（２）、（３）式中の v と u をそれぞれ無視することによって、以下のように流量フラックスを水位勾配（$I_e=\partial H/\partial x$ もしくは $\partial H/\partial y$）の関数として計算する。

$$q_x=-\frac{1}{n}h^{5/3}\sqrt{|I_e|}\,\mathrm{sgn}(I_e) \quad \cdots \quad (4)$$

$$q_y=-\frac{1}{n}h^{5/3}\sqrt{|I_e|}\,\mathrm{sgn}(I_e) \quad \cdots \quad (5)$$

ここに sgn は符号関数であり、水位勾配が正の場合は１をとり、水位勾配が負の場合は－１をとる。すなわち水位勾配が正の場合は q_x や q_y が負の値を取り、水位勾配が負の場合は q_x や q_y が正の値を取って水位の低い方向に水が流れる。

RRI モデルはデカルト座標系に基づくグリッドセルモデルであり、（１）式の連続式を

$$\frac{\partial h^{i,j}}{\partial t}+\frac{q_x^{i,j-1}-q_x^{i,j}}{\Delta x}+\frac{q_y^{i-1,j}-q_y^{i,j}}{\Delta y}=r^{i,j} \quad \cdots \quad (6)$$

のように離散化する。ここに$\left(q_x^{i,j}, q_y^{i,j}\right)$はグリッドセル($i$、$j$)からそれぞれ x 方向、y 方向に流出するフラックスを意味する。

【不飽和・飽和地中流、表面流モデルによる側方地中流の考慮】

上述の（４）、（５）式は表面流のみを考慮するモデルである。RRI モデルは、（４）、（５）式を以下のように置き換えることによって、地中の側方流と表面流とを一体的に解析する。

$$q_x = \begin{cases} -k_c I_e d_c \left(\dfrac{h}{d_c} \right)^{\beta}, & (0 \le h \le d_c) \\ -k_c I_e d_c - k_a I_e (h - d_c), & (d_c < h \le d_s) \\ -k_c I_e d_c - k_a I_e (h - d_c) - \dfrac{\sqrt{|I_e|}}{n} \mathrm{sgn}(I_e)(h - d_s)^{\frac{5}{3}}, & (d_s < h) \end{cases} \quad \cdots (7)$$

ここに、β は k_s/k_c であり、大空隙部の飽和透水係数 k_s とマトリクス部の飽和透水係数 k_c との比である。また、d_s は土壌中の最大水分量に対応する水深高さ、d_c はマトリクス部の最大水分量に対応する水深高さである。

【グリーンアンプト式による鉛直浸透流の考慮】

鉛直浸透による雨水の損失を考慮する場合は、以下で表わされるグリーンアンプト式を用いる。

$$f = k_v \left[1 + \frac{(\phi - \theta_i) S_f}{F} \right] \quad \cdots (8)$$

ここに、k_v は鉛直方向の飽和透水係数であり、ϕ は土壌の空隙率である。また θ_i は初期飽和率、S_f はサクション、F は浸透量の累積値である。

第3章 RRIモデルを用いた洪水解析

3.1 洪水対策M/Pの整理

本プロジェクトで提案した洪水対策案の適切な組み合わせ結果を表 3.1.1 に示す。また、次頁の図 3.1.1 に各対策案を示す。RRI モデルでも同様に、各種対策を実施した場合の水位、流量縦断図および浸水区域図を整理する。

表 3.1.1 洪水対策 M/P 代替案検討の概要

No.	検討ケース	対策
1	Case 0	外力は 2011 年洪水とし、破堤を考慮する。
2	Case 0-1 現況	外力は 2011 年洪水とし、破堤はないものとする。 DOH および DOR による優先防御地域の周囲堤の嵩上げ完了後を想定。
3	Case 1-1 SCWRM M/P	外力は 2011 年洪水とし、破堤はないものとする。 DOH および DOR による優先防御地域の周囲堤の嵩上げ完了後を想定。 C2: 新規ダムによる洪水調節 C4: 遊水地による洪水調節 C5-1: 堤防嵩上げ（チャオプラヤ川全川、DHWL+余裕高 50cm） C6-1: 東/西放水路（流量 1,500m^3/s） C6-2: 外郭環状道路放水路（流量 500m^3/s） C7: 既存ダムの運用ルール改善
4	Case 11-0 Proposed Combination 1	外力は 2011 年洪水とし、破堤はないものとする。 DOH および DOR による経済重要地域の周囲堤の嵩上げ完了後を想定。 C5-1: 堤防建設（チャオプラヤ川下流、DHWL+余裕高 50cm） C5-1: 堤防嵩上げ（タチン川下流、DHWL+余裕高 50cm） C5-1: ４捷水路（タチン川下流） C5-2: アユタヤバイパス水路の設置（流量 1,400m^3/s） C6-2: 外郭環状道路放水路（流量 500m^3/s） C7: 既存ダムの運用ルール改善
5	Case 11-1 Proposed Combination 2	外力は 2011 年洪水とし、破堤はないものとする。 DOH および DOR による経済重要地域の周囲堤の嵩上げ完了後を想定。 C5-1: 堤防建設（チャオプラヤ川下流、DHWL+余裕高 50cm） C5-1: 堤防嵩上げ（タチン川下流、DHWL+余裕高 50cm） C5-1: ４捷水路（タチン川下流） C5-2: アユタヤバイパス水路の設置（流量 1,400m^3/s） C6-2: 外郭環状道路放水路（流量 1,000m^3/s） C7: 既存ダムの運用ルール改善

※対策の詳細（既存ダムの運用ルール改善など）については主報告書 10 章参照。

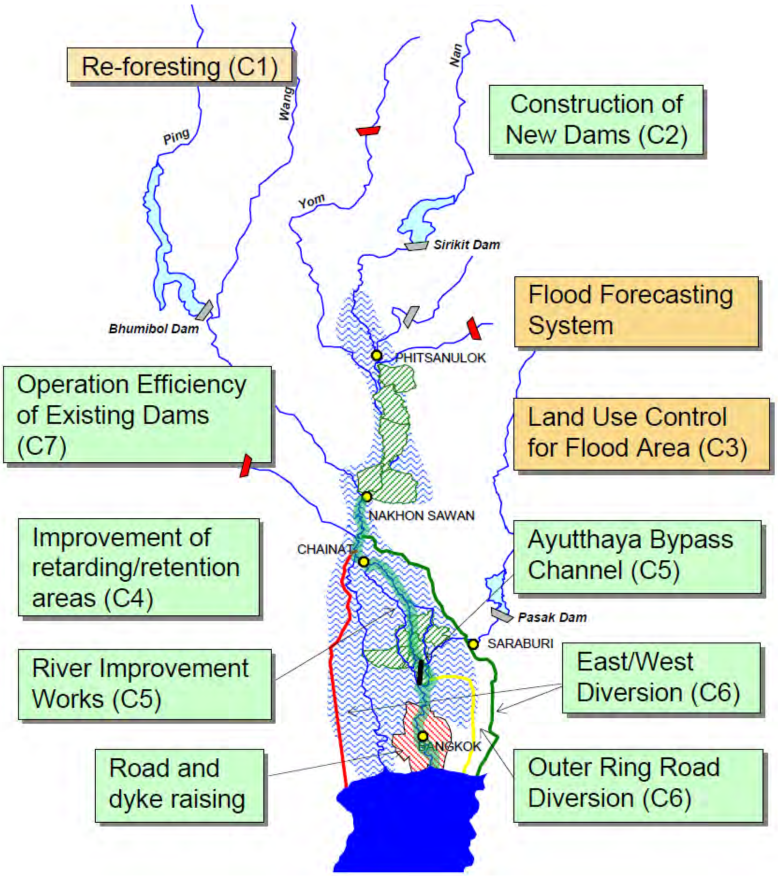


図 3.1.1　　M/P 洪水対策案

3.2 洪水解析

3.2.1 解析条件の整理

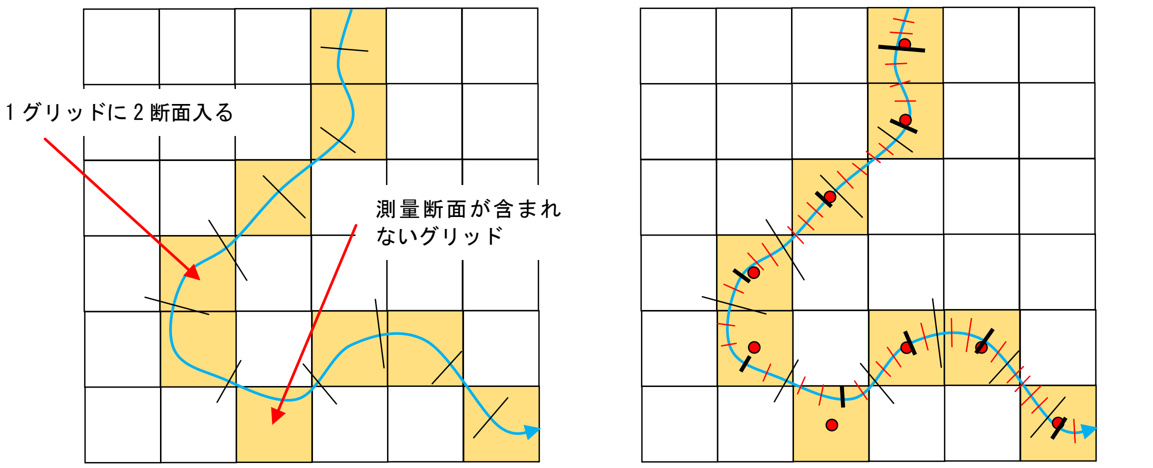
解析の基本条件を以下に整理する。

(1) 標高データ（DEM）

2012 年に JICA が別途実施した航空測量（LiDAR データ）の DEM データを使用する。グリッドサイズは 60 秒（約 1,800m）とした。LiDAR データの範囲外の標高データは、1/50,000 地形図のスポット標高をベースに補完を行った。

(2) 河道データ

河道データは、MIKE-11 の計算で用いた横断測量成果を用いる。RRI モデルでは、1 つの計算グリッドにつき、1 つの断面特性を入力する。横断測量地点とグリッドの中心は必ずしも一致しないことから、横断データから作成した断面特性をそのまま RRI モデルに入力することはできない。そこで図 3.2.1 に示す方法で各計算グリッドに断面特性を与えた。今回検討した RRI モデルは、グリッドサイズが 60 秒（約 1,800m）、横断測量の測量ピッチが 1,000m（チャオプラヤ川、タチン川下流の一部は 1,000 未満）であることから、側線間を 10 分割して各計算グリッドの代表断面を作成した。



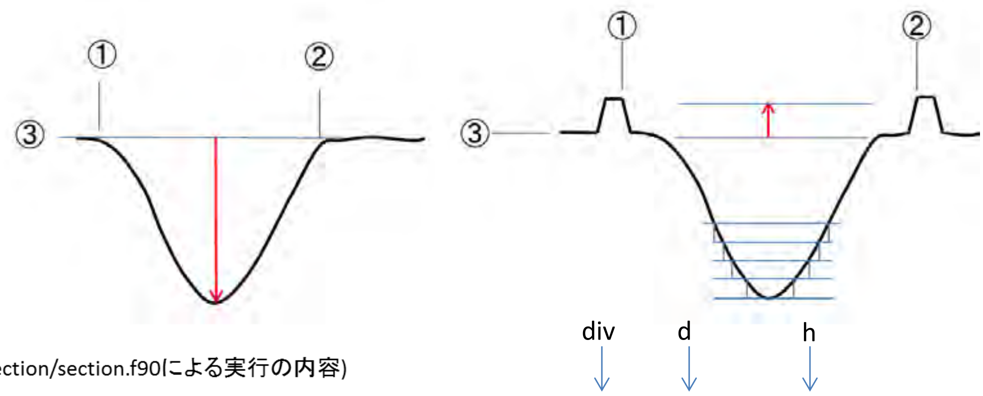
1 つのグリッドに 2 断面以上の横断側線が含まれる場合や、逆にグリッド内に側線が含まれない場合が考えられるため、各グリッドを代表する断面特性の設定が必要。

内挿断面を作成し（上図の例では 5 分割）、測量横断面を含めた全ての断面から、各グリッドのセンターに最も近い断面を（黒太線）そのグリッドの代表断面とし、断面特性を作成。今回は 10 分割（内挿断面は 9 つ）し、各グリッドの代表断面を設定。

図 3.2.1 断面特性の入力方法

(3) 断面特性データ（河道粗度係数）

断面特性のデータとして、水深 H と潤辺 S、水面幅 B、粗度係数 N を整理する。水位に応じた合成粗度係数を与えることができるため、低水路と高水敷の粗度係数の違いについても考慮可能である。粗度係数については MIKE-FLOOD で設定した低水路/高水敷粗度を用いて、水深に応じた合成粗度係数を与える。



(etc/section/section.f90による実行の内容)

STEP 1 : 深さ(d), 堤防高(h) を測る
（深さは③から最深点までの高低差、堤防高は③から①もしくは ②の高低差で小さい方）

STEP 2 : 最深点から最高点までをdiv（例: 100）で等分する

STEP 3 : 各水深に対する、径深、幅 を出力する
（断面積はRRI内で計算）
（粗度は、現状はプログラムに書き込んでいるので要修正）

→ 合成粗度係数作成プログラムは別途 JICA 調査団が作成

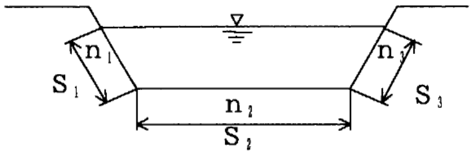
100　10.98000　0.00000

水深	径深	幅	当該水深に対する合成粗度
0.11339	23.78646	23.77967	0.03000
0.22678	27.57293	27.55933	0.03000
0.34017	31.35939	31.33900	0.03000
0.45356	35.14586	35.11867	0.03000
（中省略）			
11.11222	298.35455	295.76846	0.03000
11.22561	298.56949	295.95105	0.03000
11.33900	300.62881	298.00000	0.03000

図 3.2.2　断面特性データの解説（ICHARM 佐山氏提供）

【単断面の場合】

$$N = \left(\frac{\sum_{i=1}^{m} \left(n_i^{3/2} \cdot S_i \right)}{S} \right)^{2/3}$$



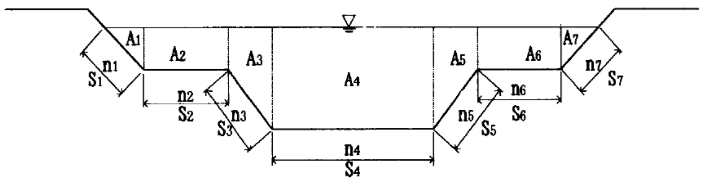
$$S = S_1 + \cdots + S_m$$

【複断面の場合】

$$N = \frac{A \cdot R^{2/3}}{\sum_{i=1}^{n} \left(\frac{A_i}{n_i} \cdot R_i^{2/3} \right)}$$

$$A = \sum A_i$$

$$R = \frac{A}{S} = \frac{\sum A_i}{\sum S_i}$$



N：合成粗度係数、n_i：各部位の粗度係数、S：各部位の潤辺の合計、s_i：各部位の潤辺、A_i：各部位の面積、A：各部位の面積の合計、R：径深

出典：中小河川の手引き（財）国土開発技術研究センター

図 3.2.3　合成粗度係数の算定方法

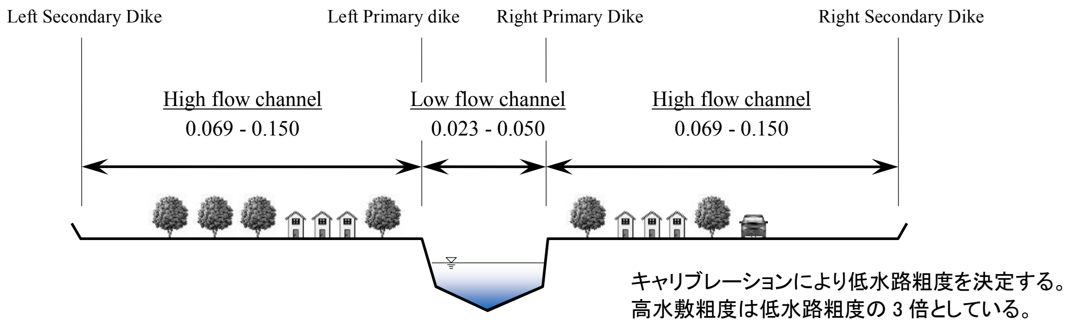


図 3.2.4　河道粗度係数（MIKE-11 と同一）

(4)　水路データ

RRI モデルでは、任意の集水グリッド数をベースに水路データ（矩形断面、水路幅 *B* と水深 *H* で定義）を設定することが可能である。集水グリッド数とは、任意のグリッドについて、流入が見込まれるグリッドの数の合計である。右図の場合、青色のグリッドの集水グリッド数は 8 つである。通常、集水グリッド数が大きいほど、水路幅は大きくなる。

本調査では集水グリッド数が 50 以上のグリッドを河道グリッドとして定義し、矩形断面情報を与えた。

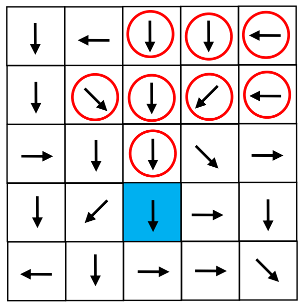


図 3.2.5　集水グリッド数

水路幅 *W*、および水深 *D* は、集水グリッド数から求められる集水面積 *A*（km^2）からの以下の式で求める。

$$W = C_W A^{S_W} 、 D = C_D A^{S_D}$$

ここで、C_W、S_W、C_D、S_D は河道パラメータとして定義する。チャオプラヤ川流域では、C_W=16.93、S_W=0.186、C_D=2.48、S_D=0.12 が ICHARM によって提案されている[1]。

(5)　堤内地粗度係数

各グリッドに粗度係数を与えることが可能である。本計算では、ナコンサワン上流を 11 流域に分割し、各流域で市街地と自然地の 2 つの粗度係数を設定した。ナコンサワン下流については、1 つの粗度係数を与えた

(6)　地下水パラメータについて

ナコンサワン（C.2）上流については、地形勾配があることから Darcy 則に基づいた側方浸透を考慮する。ナコンサワン（C.2）下流については、地形勾配がフラットで、鉛直方向の浸透が支配的であると考えられるため、グリーンアンプト式を用いた鉛直方向の浸透流を考慮する。

[1] 土木学会論文集 B1(水工学), Vol. 69　2011 年タイ洪水を対象にした緊急対応の降雨流出氾濫予測

(7)　計画対象洪水

2011 年洪水の降雨を計算グリッドに与える。

(8)　下流端境界

2011 年の潮位データを与える。チャオプラヤ川については、Pom Phrachul 検潮所のデータを、タチン川については Samut Sakon 検潮所のデータを下流端にそれぞれ与えた。

3.2.2 洪水解析ケース

下表に、洪水解析ケースの一覧を示す。

表 3.2.1　解析ケース一覧

	タイ側が実施中の洪水対策		洪水対策案						
			C7	C2	C4	C5			C6
Case	優先防御地域周囲の堤防嵩上げ考慮	BMA、DOHによるチャオプラヤ川およびパサック川の堤防嵩上げ	既存ダムの運用効率化	新ダムの建設	遊水地/調整池の改善	DHWL+余裕高（50cm）の高さまで堤防嵩上げ	放水路の建設（東側・西側）	アユタヤバイパス水路	外郭環状道路放水路
0									
0-1	●	●							
1-1	●	●	●	●	●	●	● 1,500m^3/s	●	● 500m^3/s
11-0	●	●	●					●	● 500m^3/s
11-1	●	●	●					●	● 1,000m^3/s

※表中の流量は放水路の流下能力を示す。
※Case 0 では破堤を考慮し、それ以外のケースでは破堤は生じないものとする。

3.2.3 解析結果

前述の解析条件をもとに、各ケースの洪水解析を実施した。次頁から流量縦断および主要観測所のハイドログラフ、浸水想定区域図を示す。

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株式会社建設技術研究所

(1)　計算結果（Case 0：2011 年洪水再現計算）

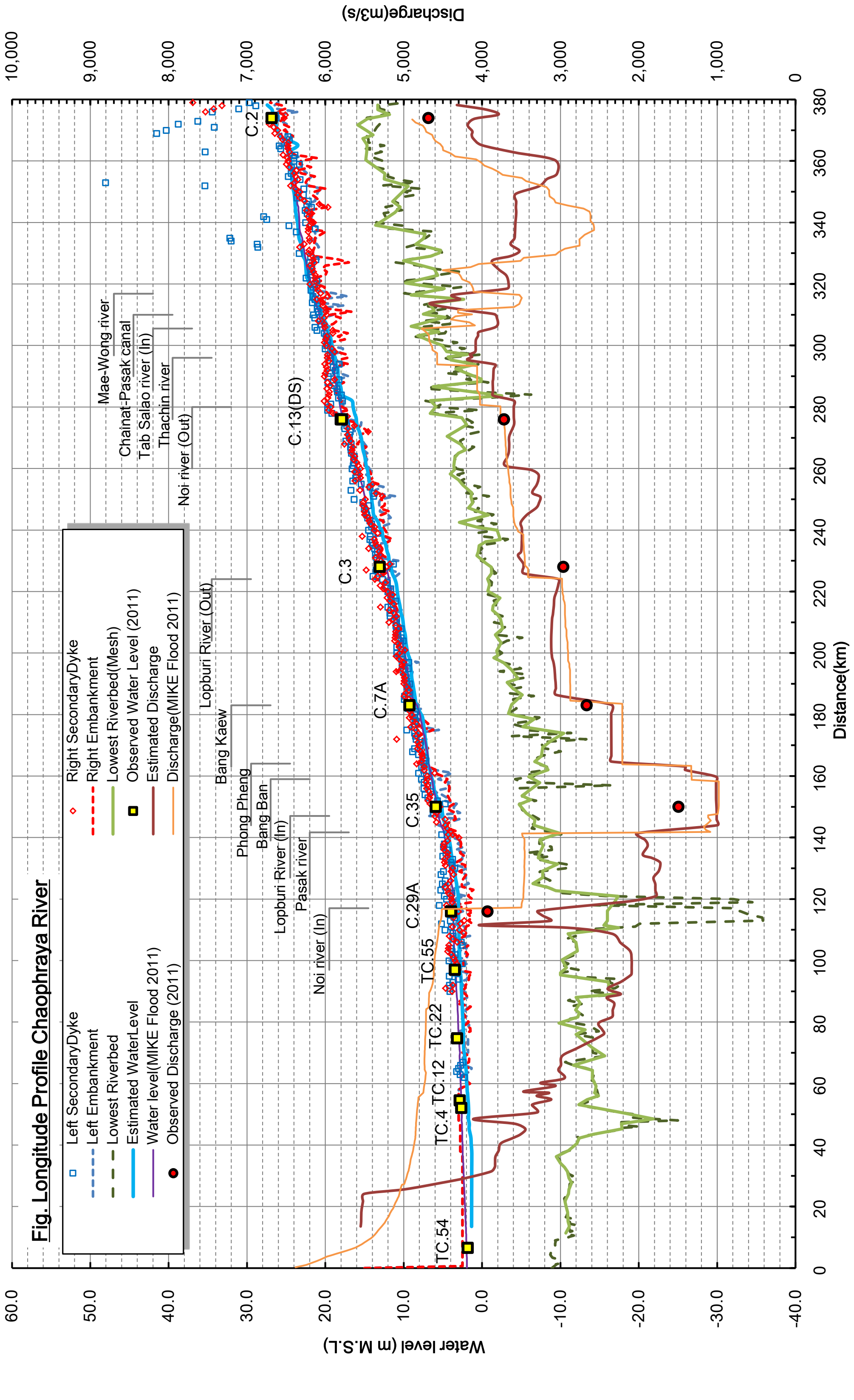

図　3.2.6　　水位流量縦断図（Chao Phraya River）

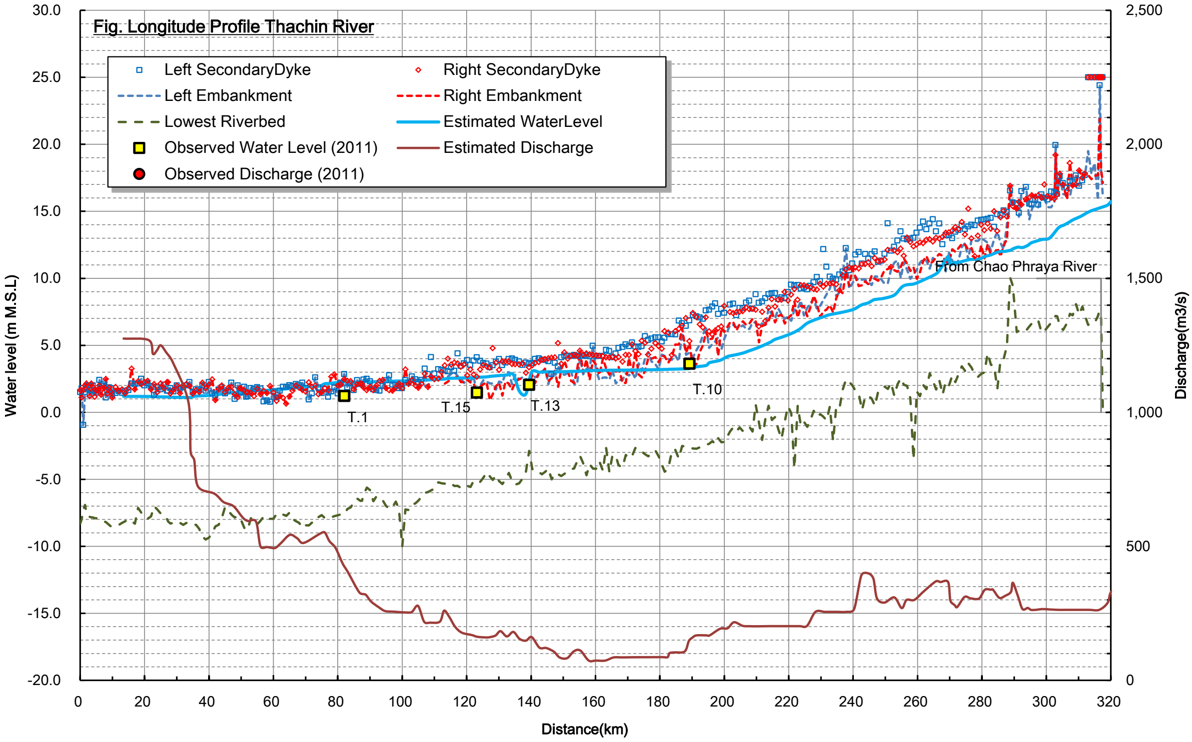

図 3.2.7　　水位流量縦断図（Tha Chin River）

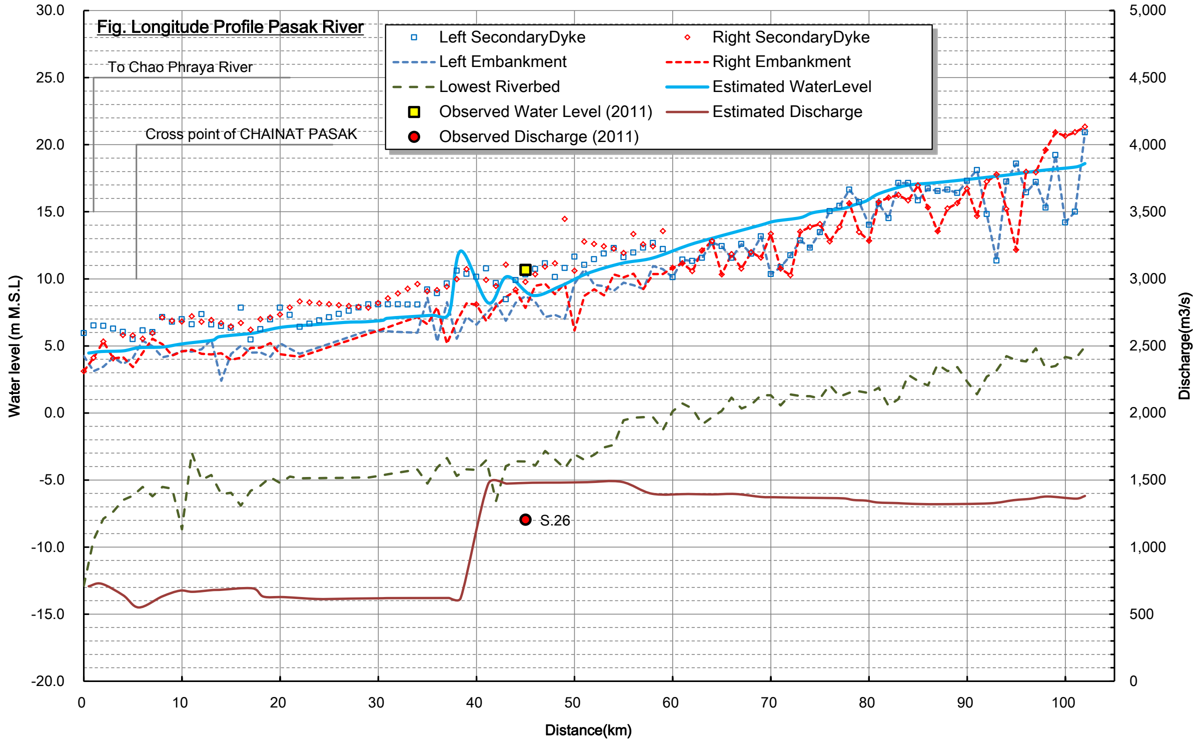

図 3.2.8　　水位流量縦断図（Pasak River）

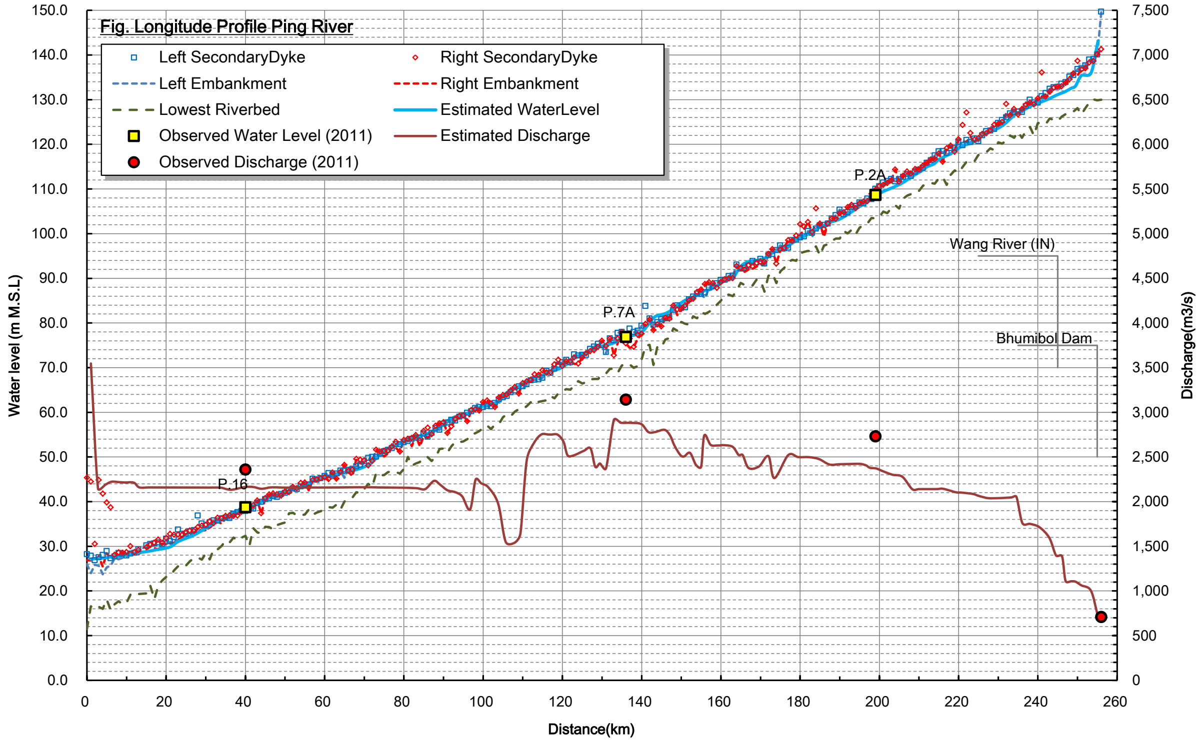

図 3.2.9　水位流量縦断図（Ping River）

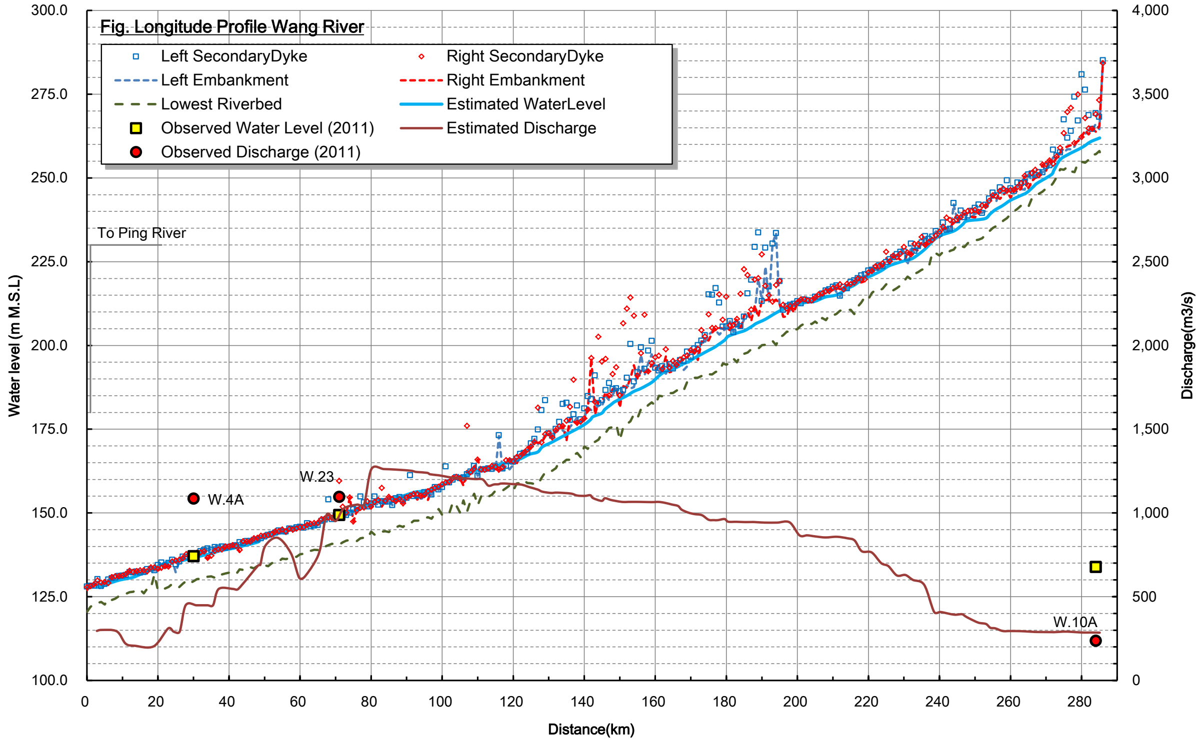

図 3.2.10　水位流量縦断図（Wang River）

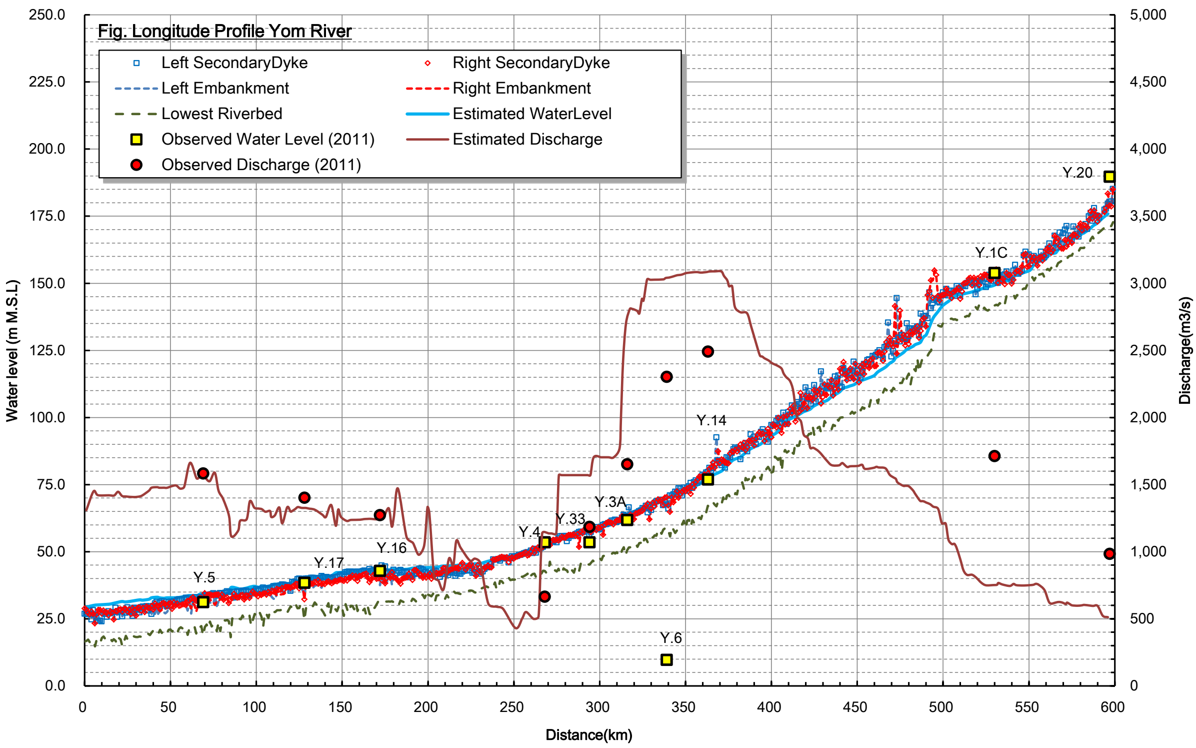

図 3.2.11　水位流量縦断図（Yom River）

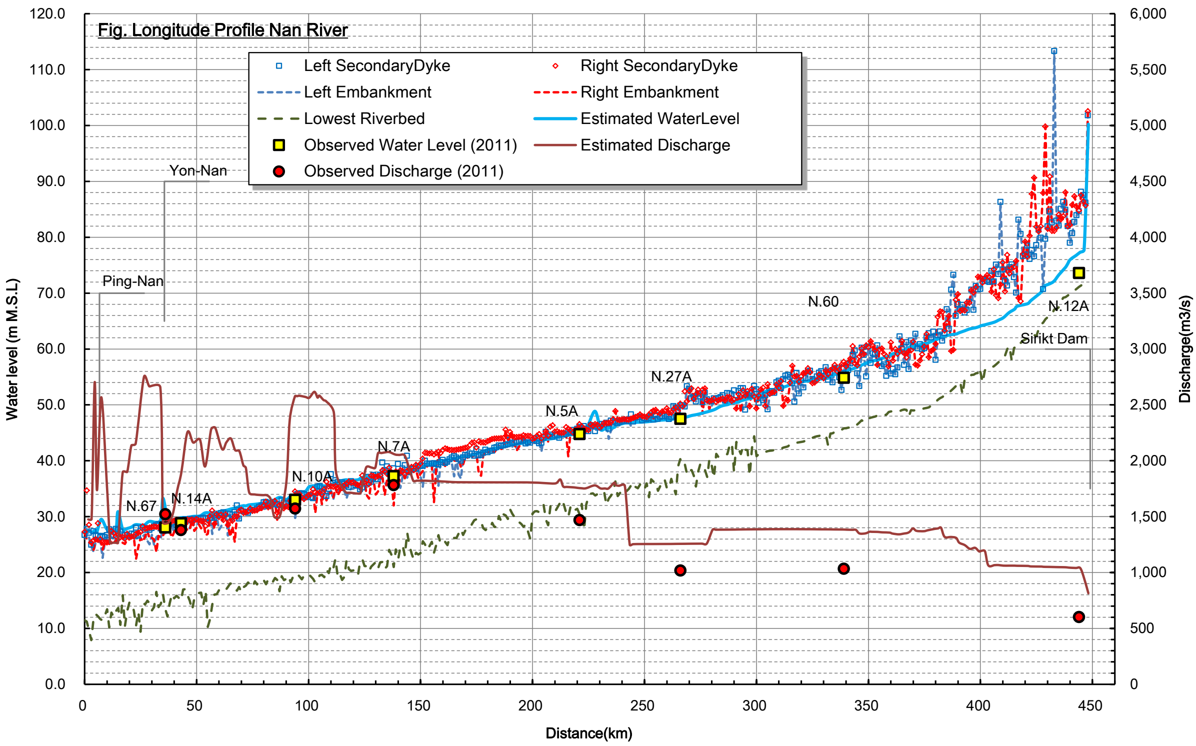

図 3.2.12　水位流量縦断図（Nan River）

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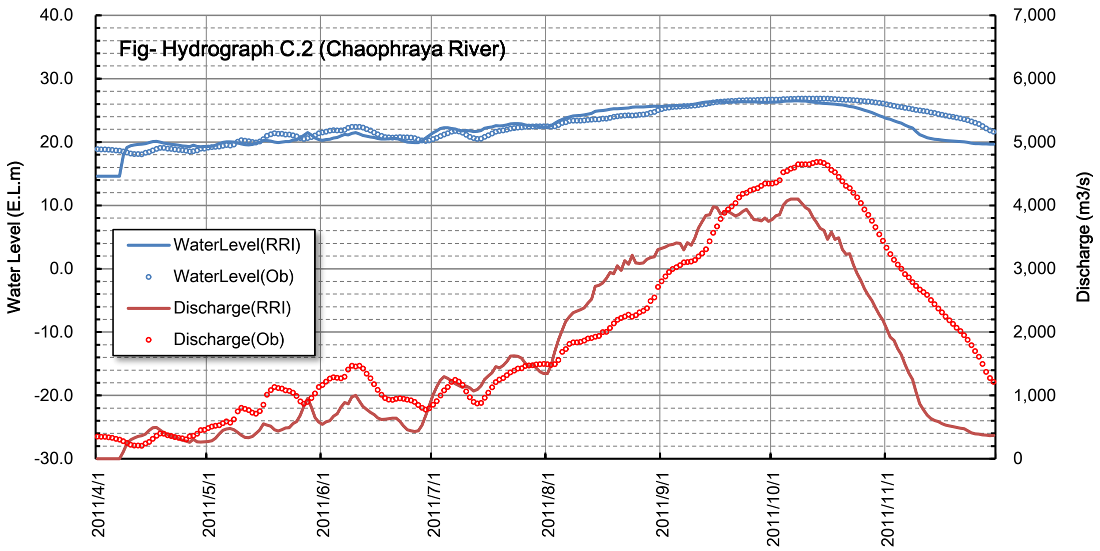

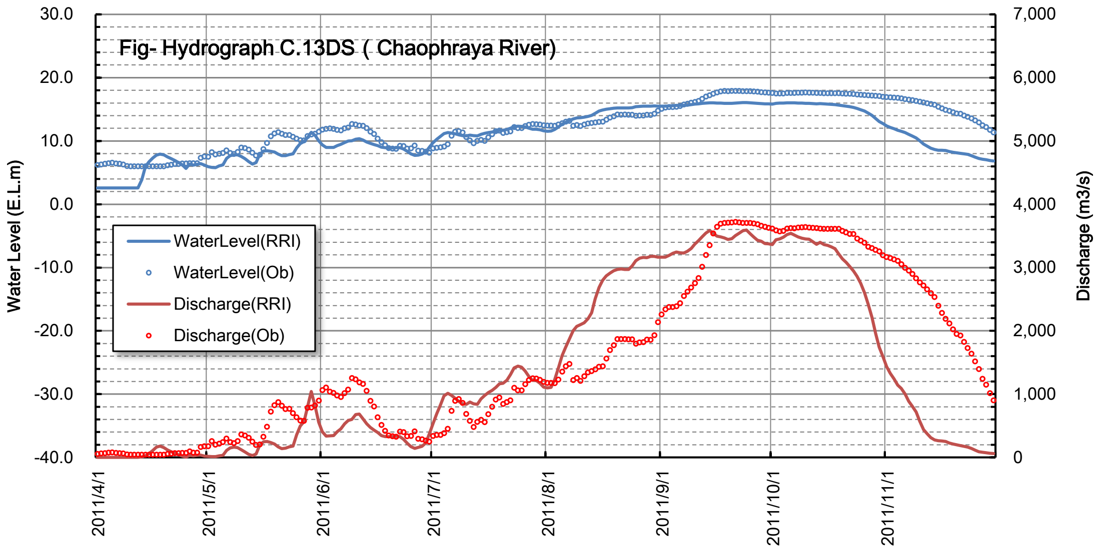

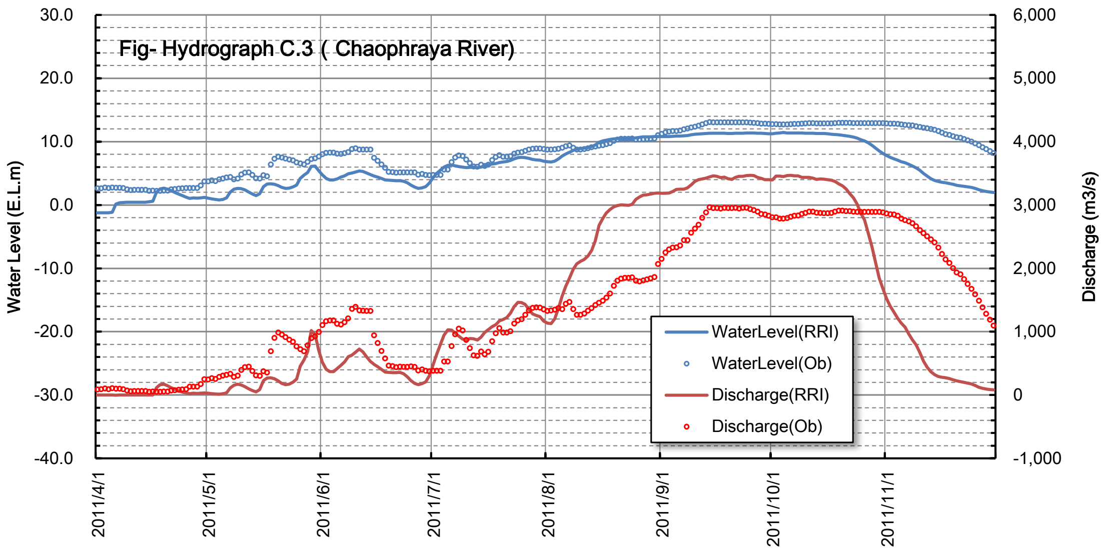

図 3.2.13　主要地点ハイドログラフ（1）

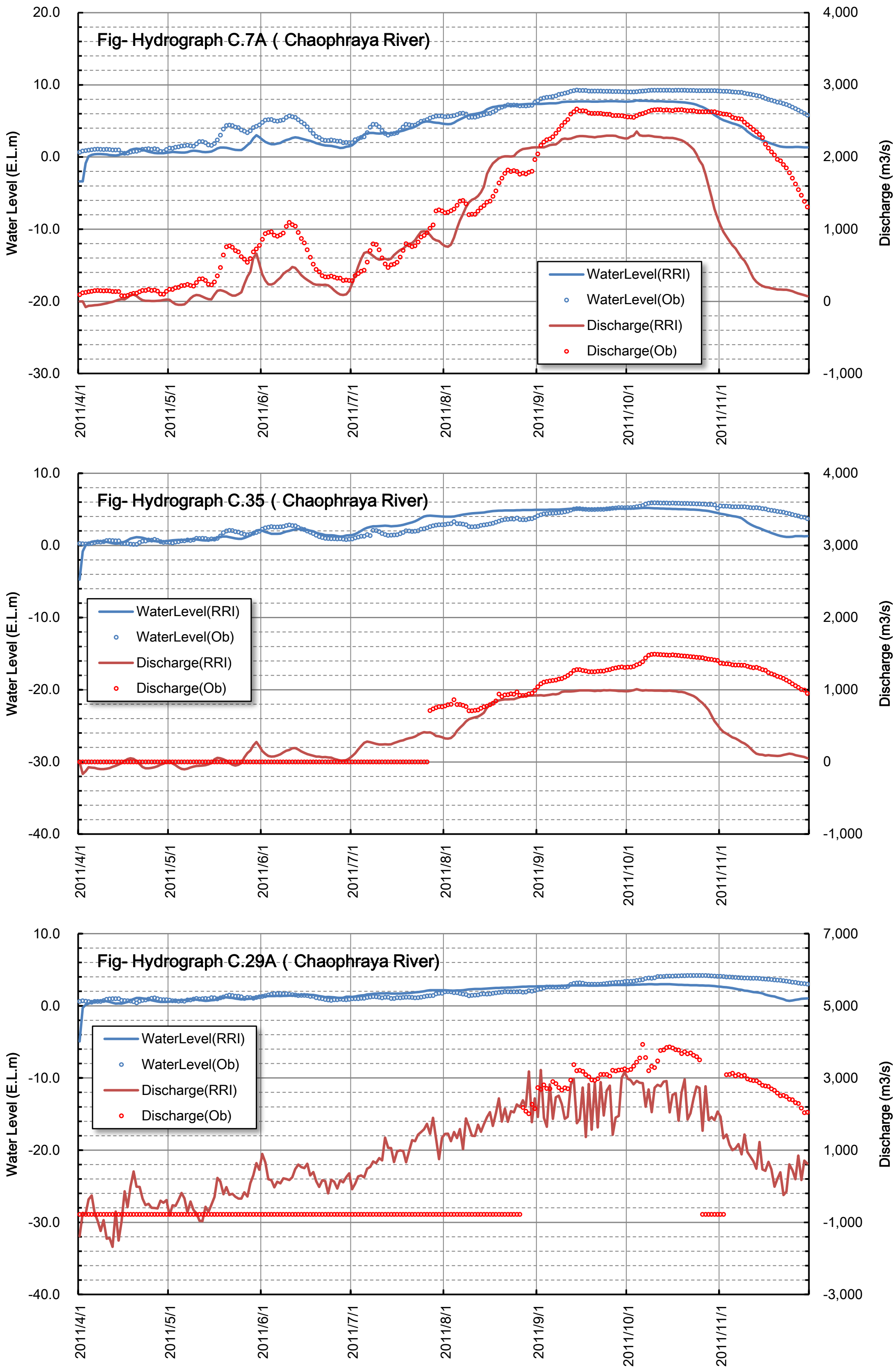

図 3.2.14　主要地点ハイドログラフ（2）

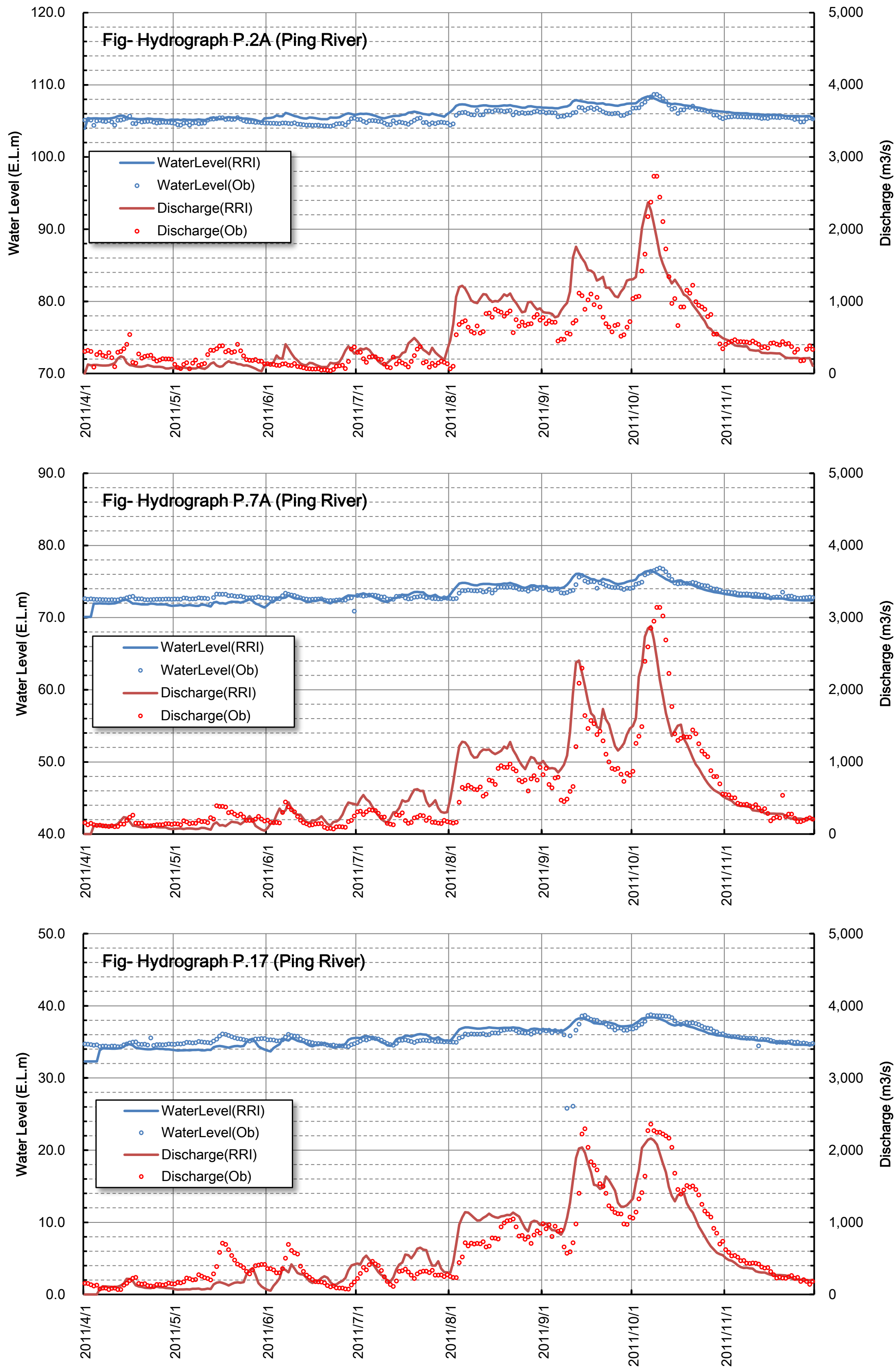

図 3.2.15　主要地点ハイドログラフ（3）

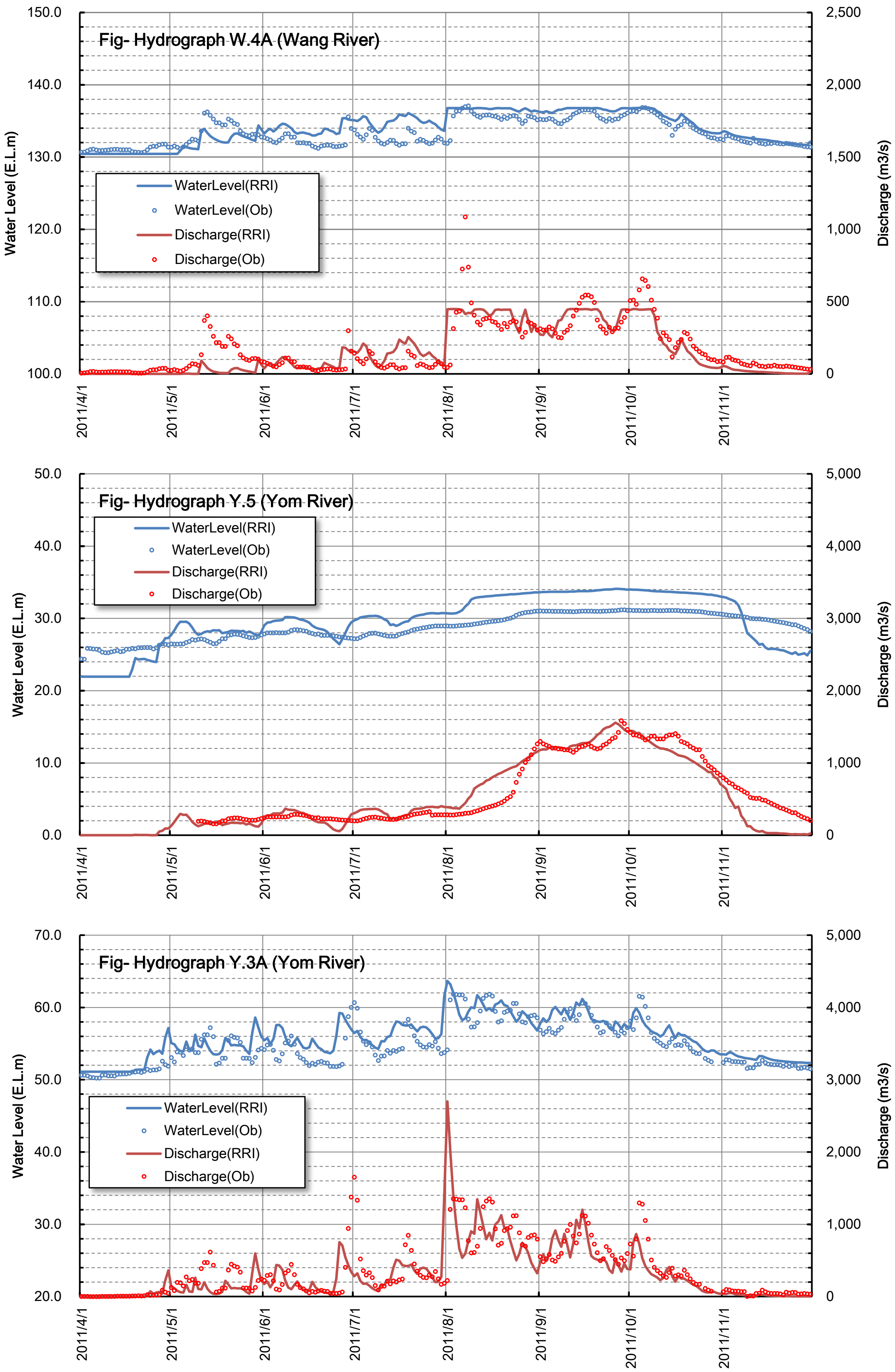

図 3.2.16　主要地点ハイドログラフ（4）

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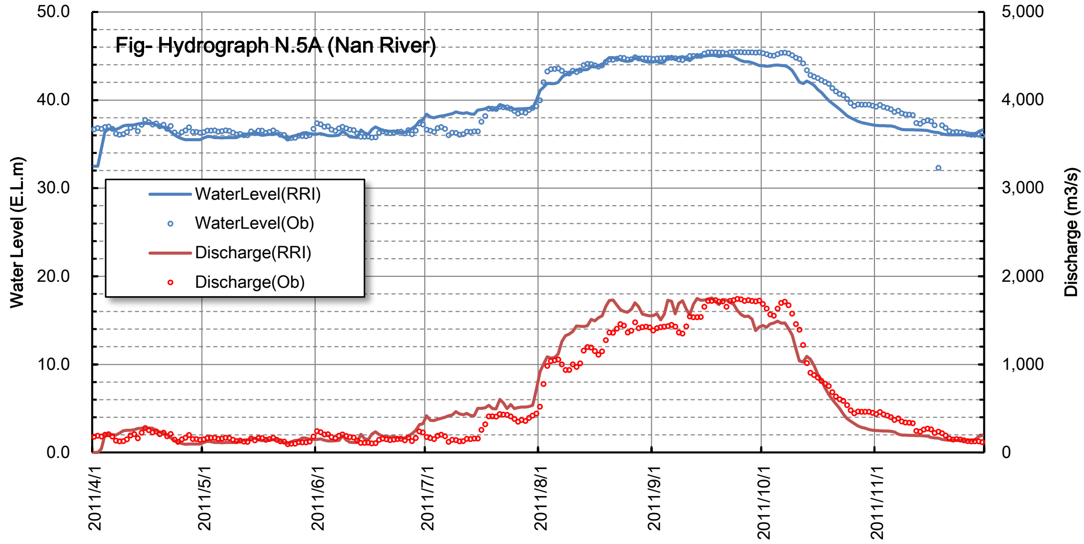

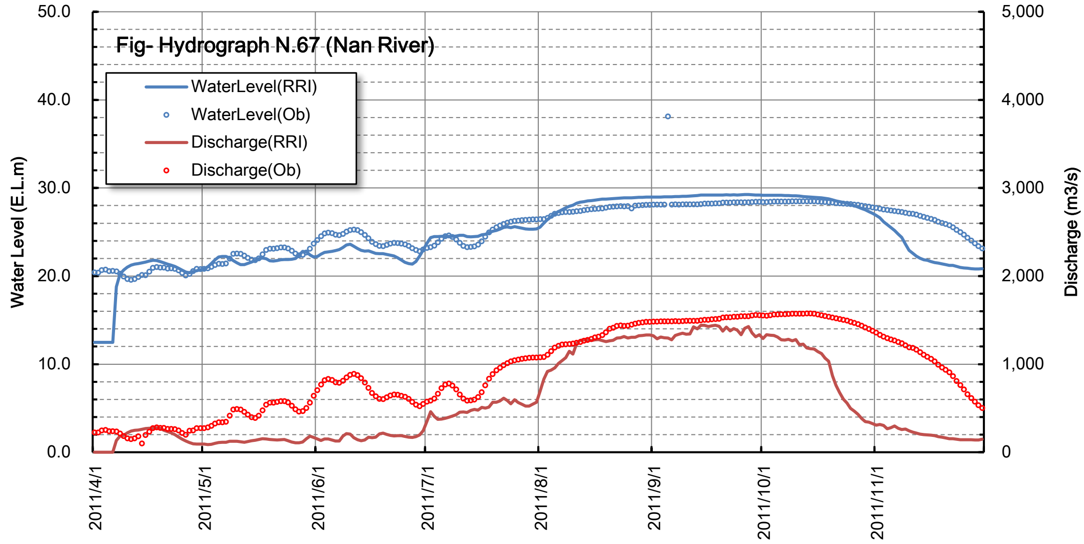

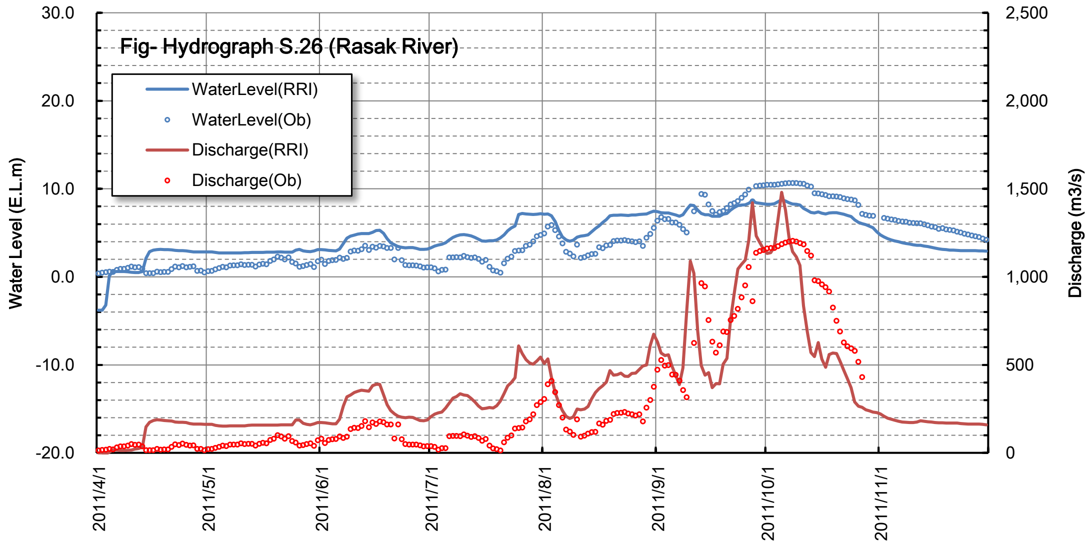

図 3.2.17　主要地点ハイドログラフ（5）

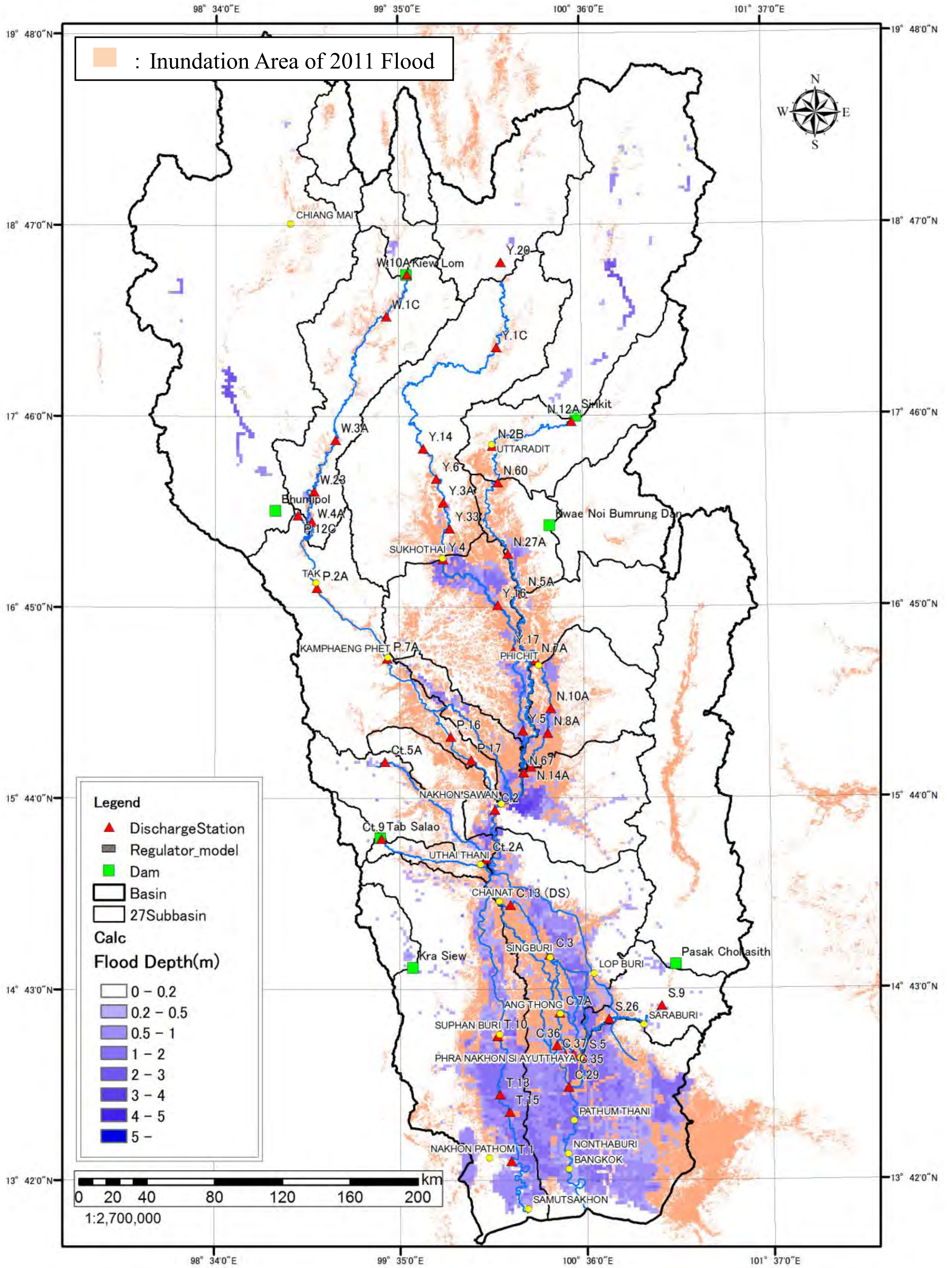

図 3.2.18　最大浸水深図（Case 0）

(2) 計算結果（Case 0-1：現況）

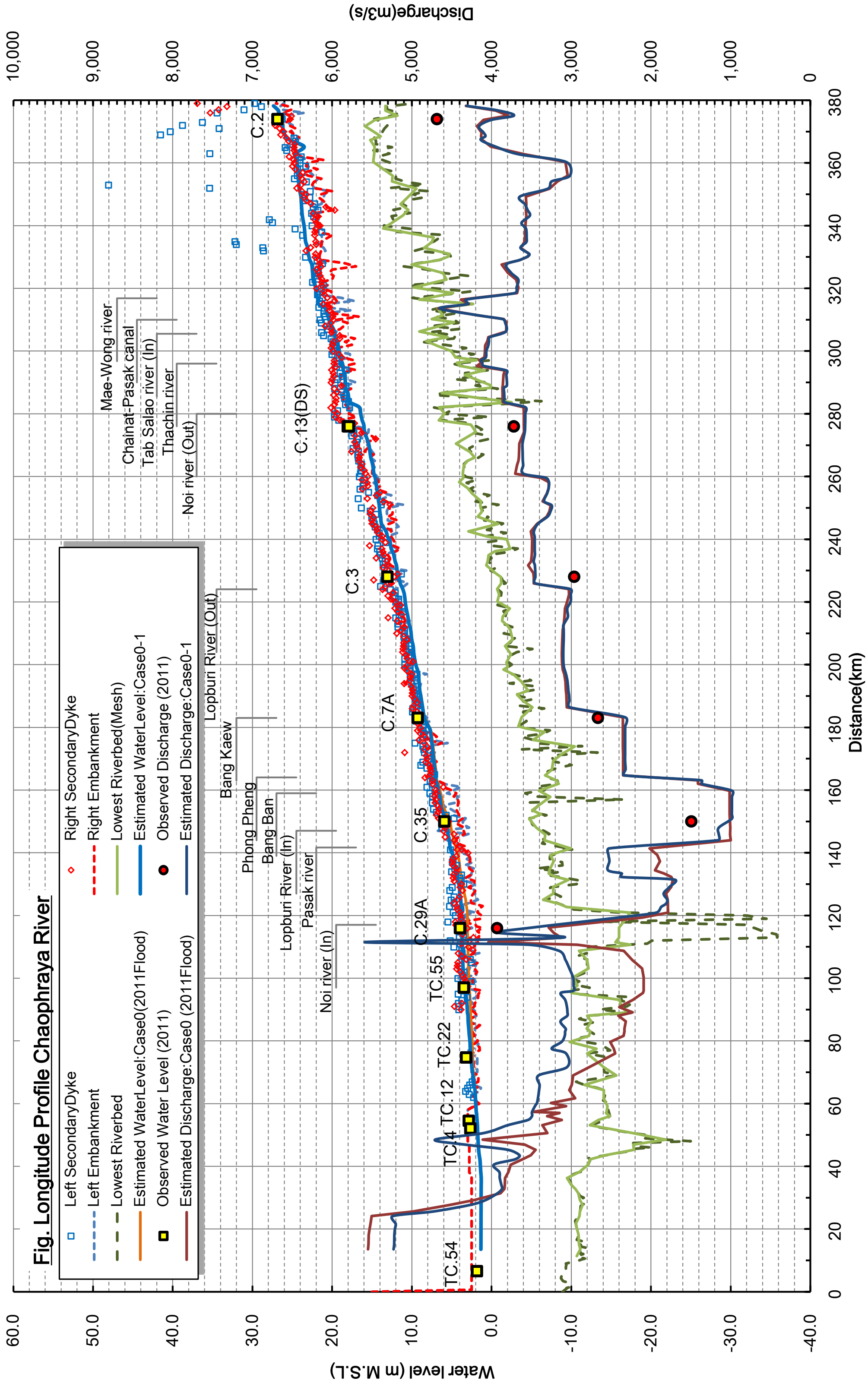

図 3.2.19 水位流量縦断図（Case 0-1）

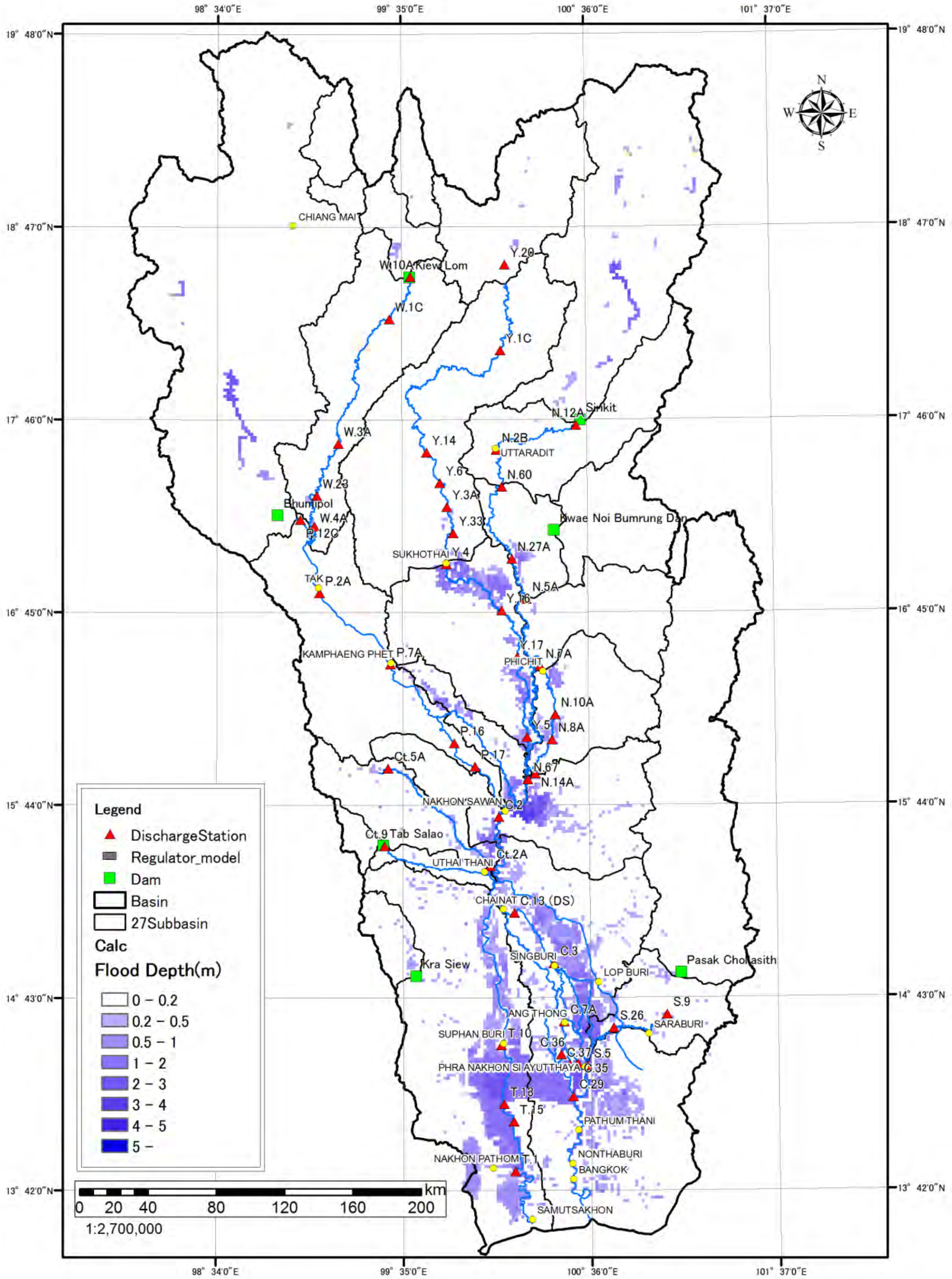

図 3.2.20 最大浸水深図（Case 0-1）

(3) 計算結果（Case 1-1：SCWRM M/P Full Menu）

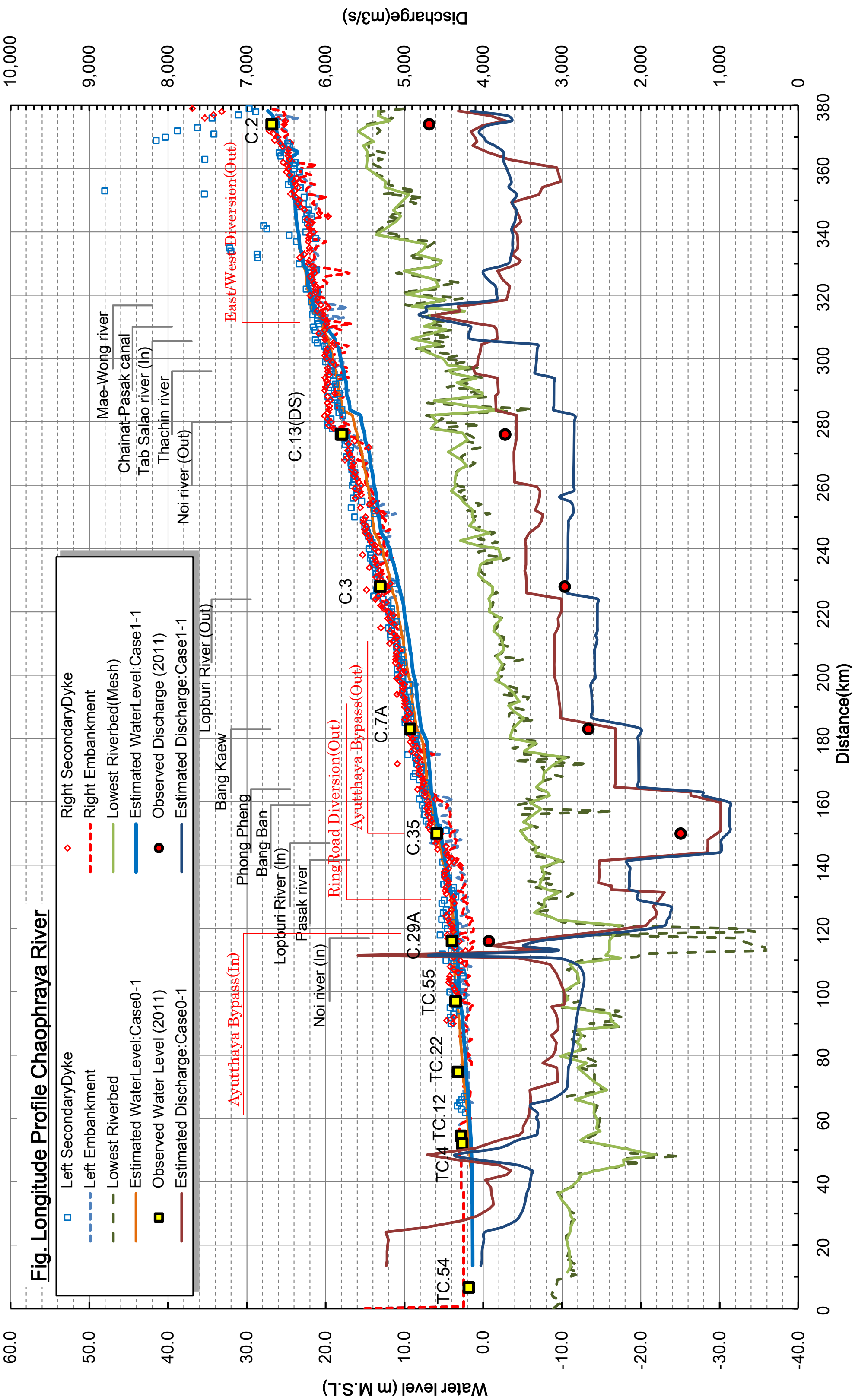

図 3.2.21 水位流量縦断図（Case 1-1）

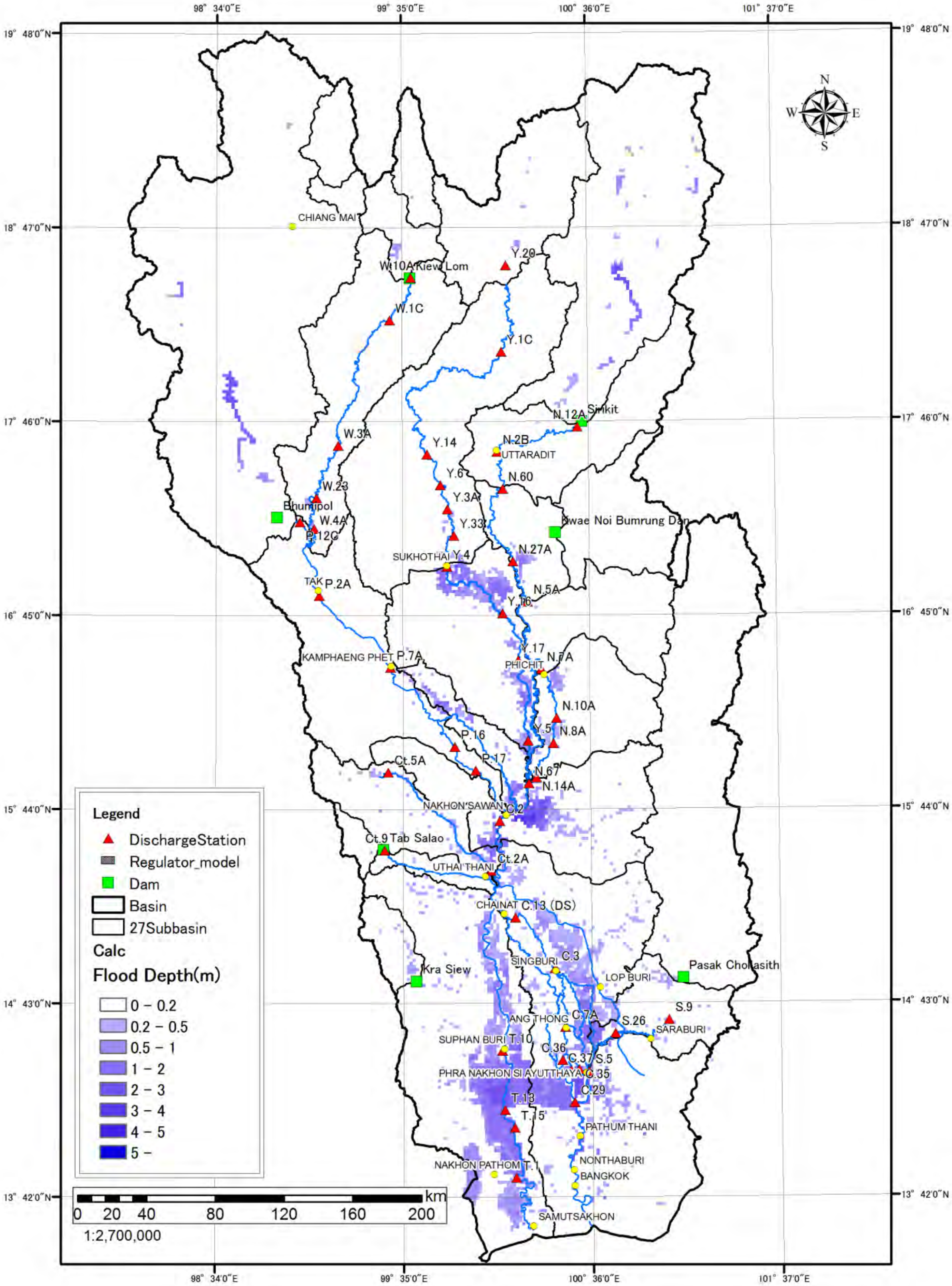

図 3.2.22 最大浸水深図（Case 1-1）

(4)　計算結果（Case 11-0：Proposed Combination 1）

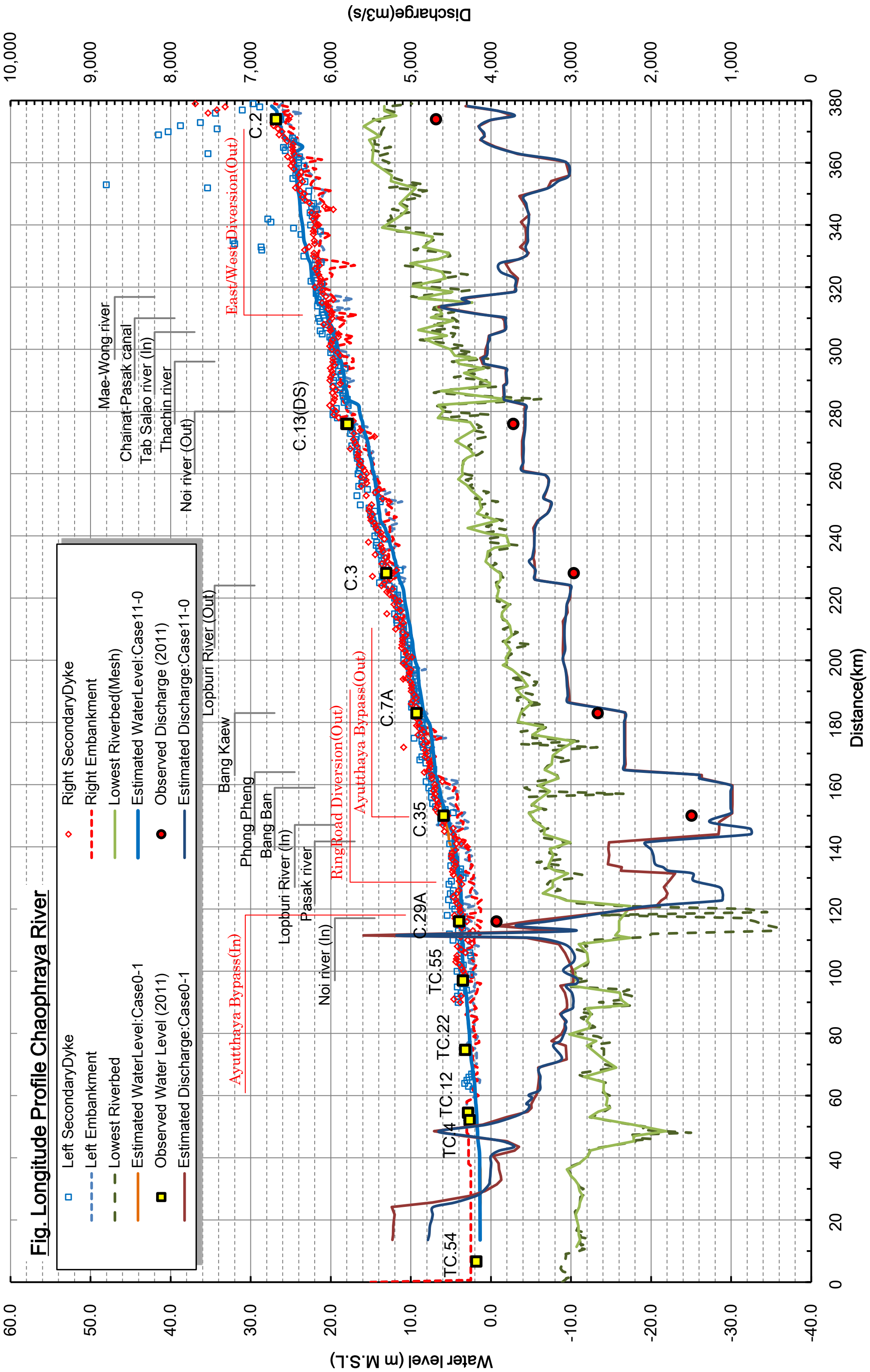

図 3.2.23　水位流量縦断図（Case 11-0）

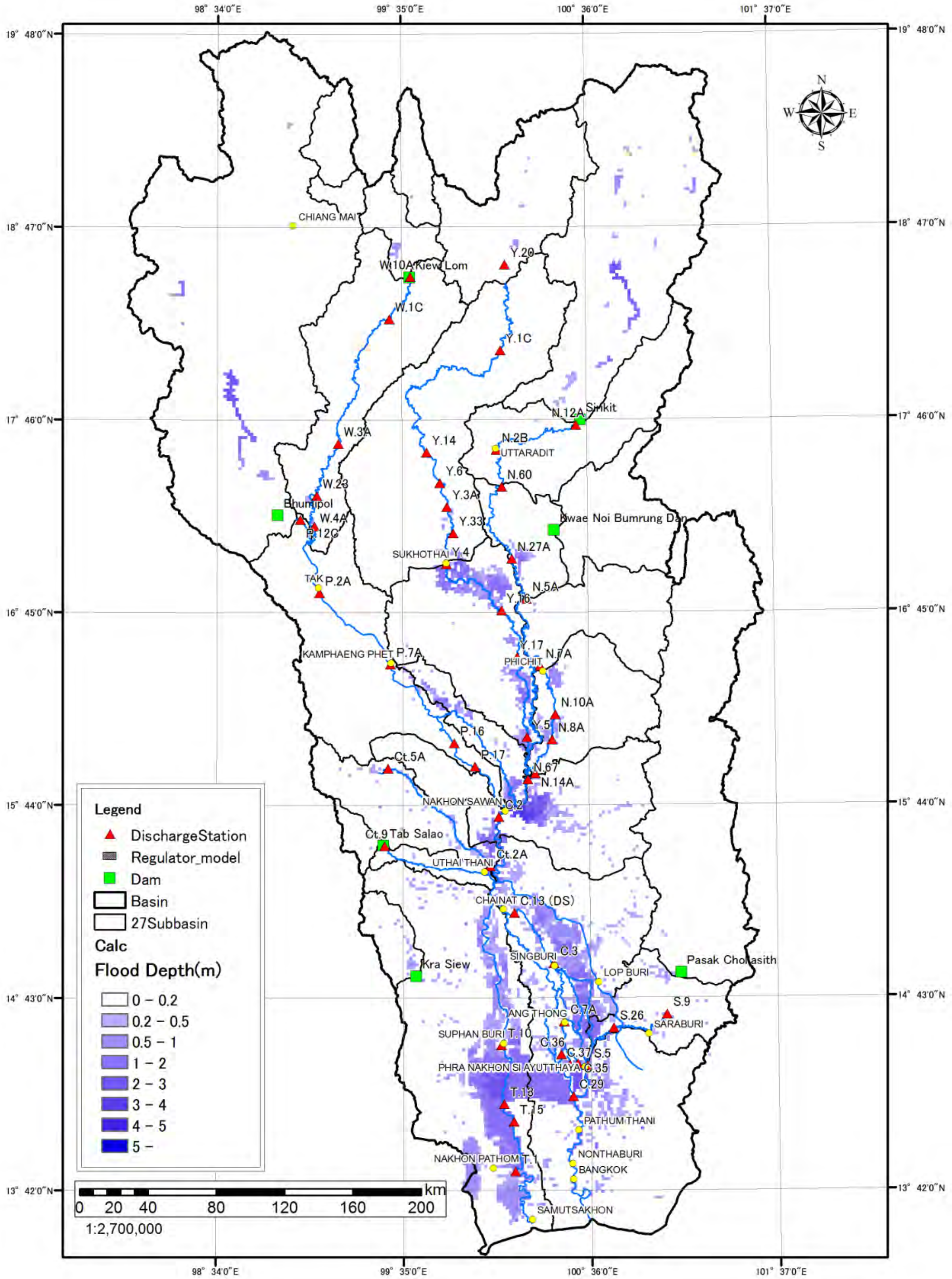

図 3.2.24　最大浸水深図（Case 11-0）

(5) 計算結果（Case 11-1：Proposed Combination 2）

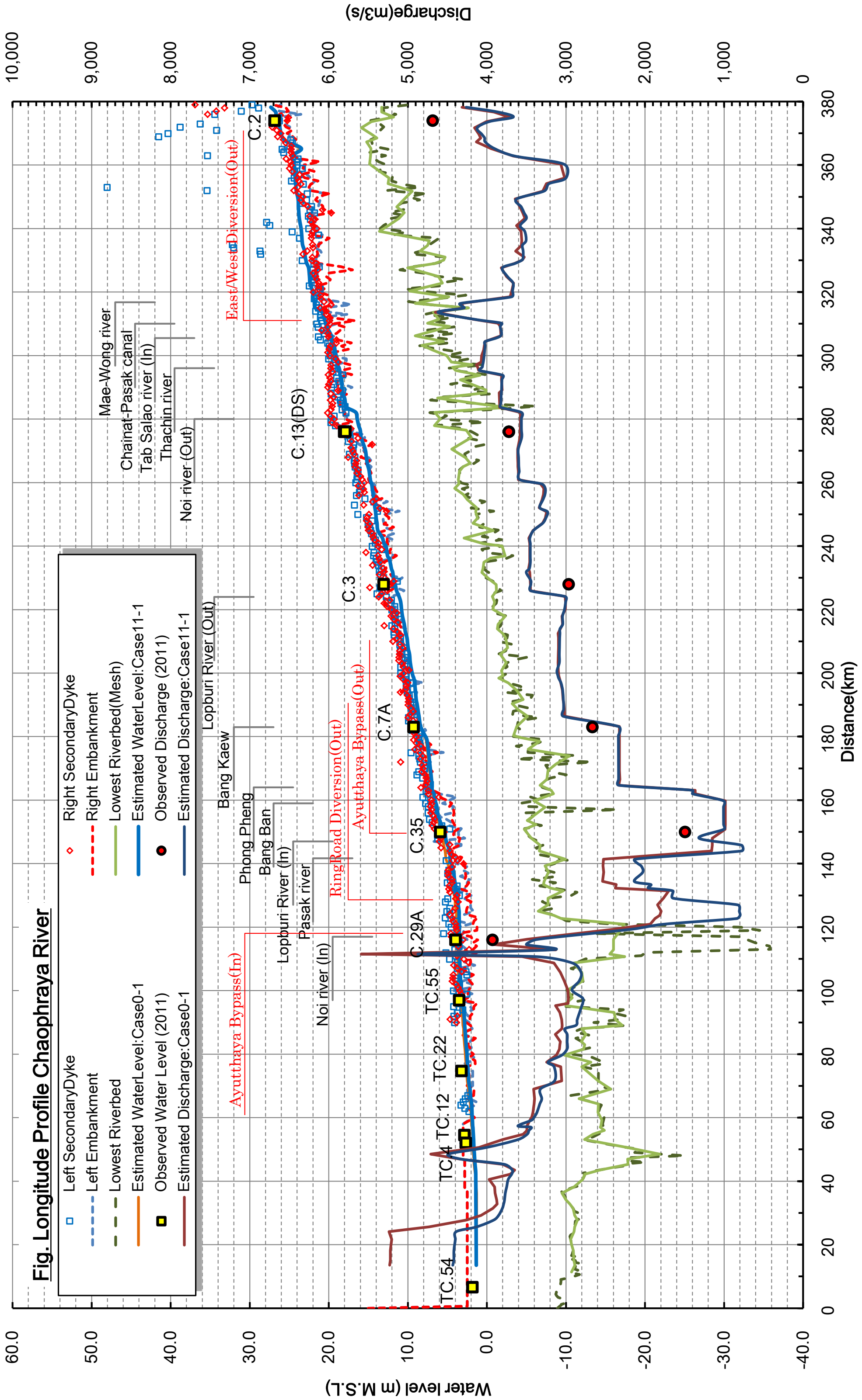

図 3.2.25 水位流量縦断図（Case 11-1）

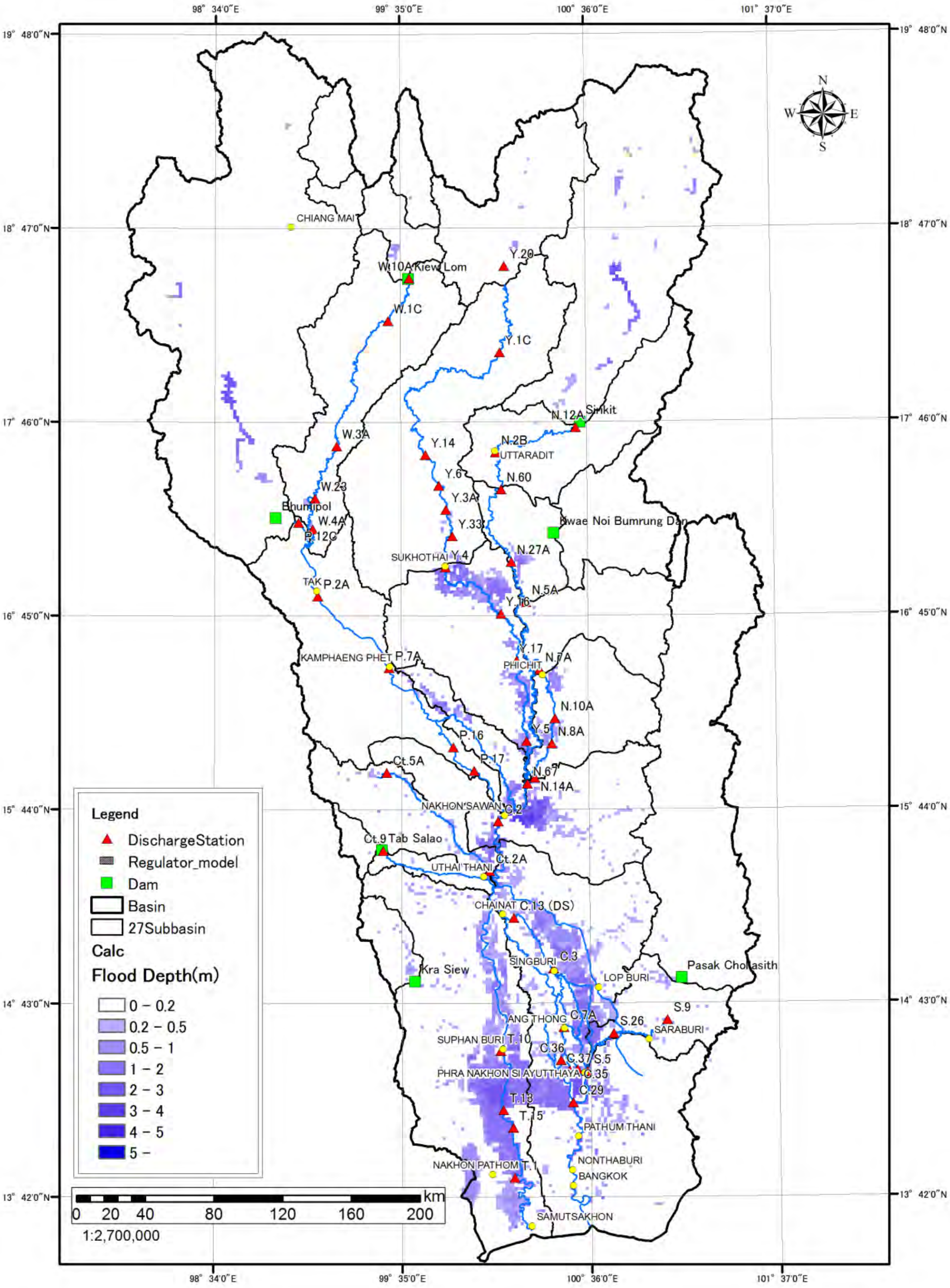

図 3.2.26 最大浸水深図（Case 11-1）

3.3　考察および今後の展望

(1)　解析結果の評価

- 2011 年洪水における主要な水位観測所のハイドログラフは概ね再現されている。ピン川をはじめとするナコンサワン（C.2）地点上流の河川については、洪水ピーク、洪水波形ともに再現性は良好である。
- 浸水範囲についても概ね 2011 年洪水の実績を再現している。ただし、モデルの構造上、左右岸個別に越流ボリュームを与えることができないため、浸水範囲の再現性が低い箇所が部分的に存在する。なお、左右岸別々の越流を考慮するために、河川沿いの計算グリッドの標高を堤防高程度まで上げて表現する方法があり、洪水予測システムに導入されている RRI モデルは、この手法で左右岸別の越流を考慮している（グリッドサイズは 900m）。

(2)　RRI モデルの実用性の評価（2013 年時点）

- RRI モデルにおける主なパラメータは、河道粗度係数、堤内地粗度係数、透水係数である。パラメータ調整箇所が少ないにも関わらず、良好な再現計算結果を得られる点を考慮すると、RRI モデルの実用性は高く、途上国の洪水解析に有用であると判断できる。
- 河川横断構造物のモデル化ができないことから、チャオプラヤダムといった河川横断構造物周辺の再現性に課題が残る。
- また、現時点では分派量の計算は実績流量から求めた分派率を用いて計算しているが、観測資料が十分に存在しない河川でも計算できるように、水理解析による分派量の算定が望ましい。

(3)　今後の展望

- 河道追跡モデルの改良について：
  モデルの構造上、河道追跡モデルの大幅な変更は困難であるが、分派の自動計算やチャオプラヤダムといった河道横断構造物のモデル化等によって、より高い精度の洪水解析が期待できる。
- 越流について：
  河川沿いの標高を上げることで、左右岸別の越流を表現することは可能であるが、グリッドサイズによっては精度が問題となる。このため、左右岸個別に計算できることが望ましい。なお、破堤については河道沿いの標高を任意の時間に下げることで、左右岸別の破堤計算が可能である。

(4)　その他

2013 年 8 月時点で、FRICS は計算シミュレーター（Graphical User Interface、GUI）を開発している。このシミュレーターにより、ダム・水門等の施設操作の効果を予測する管理施設操作シミュレーション、破堤等を仮定しての浸水拡大の影響や大規模な土嚢による臨時の堤防・緊急排水ポンプ設置による効果を予測する緊急復旧シミュレーションなどの検討が可能となる。また、このシミュレーターを使って、データ入力および編集も可能である。

添付資料

添付資料 -1 RRI モデルユーザーマニュアル

(Version 1.3)

Rainfall-Runoff-Inundation (RRI) Model

ver. 1.3

International Center for Water Hazard and Risk Management (ICHARM)
Public Works Research Institute (PWRI)

Takahiro SAYAMA

Rainfall-Runoff-Inundation Model User's Manual
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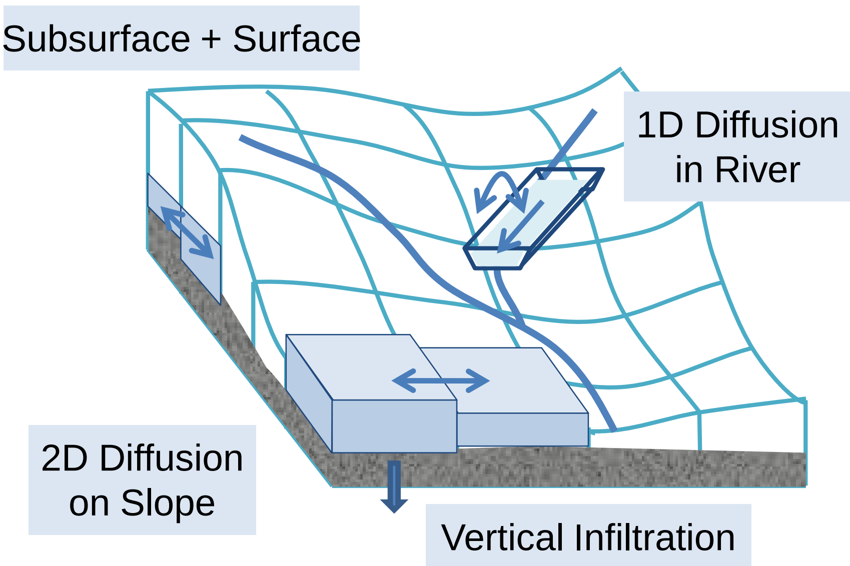
Last updated on Sep. 11, 2013

1. Outline of Rainfall-Runoff-Inundation (RRI) Model

1.1 Model Structure Overview

Rainfall-Runoff-Inundation (RRI) model is a two-dimensional model capable of simulating rainfall-runoff and flood inundation simultaneously (Sayama et al., 2012). The model deals with slopes and river channels separately. At a grid cell in which a river channel is located, the model assumes that both slope and river are positioned within the same grid cell. The channel is discretized as a single line along its centerline of the overlying slope grid cell. The flow on the slope grid cells is calculated with the 2D diffusive wave model, while the channel flow is calculated with the 1D diffusive wave model. For better representations of rainfall-runoff-inundation processes, the RRI model simulates also lateral subsurface flow, vertical infiltration flow and surface flow. The lateral subsurface flow, which is typically more important in mountainous regions, is treated in terms of the discharge-hydraulic gradient relationship, which takes into account both saturated subsurface and surface flows. On the other hand, the vertical infiltration flow is estimated by using the Green-Ampt model. The flow interaction between the river channel and slope is estimated based on different overflowing formulae, depending on water-level and levee-height conditions.



Model Features

1) Rainfall-runoff and inundation simultaneously with diffusion wave approximations.
2) Subsurface flow (lateral subsurface and vertical infiltration) is simulated for physical representations of rainfall-runoff processes.
3) One-dimensional diffusive wave river routing and its interaction with the slope model.

1.2 Governing Equations of RRI Model

A method to calculate lateral flows on slope grid-cells is characterized as “a storage cell-based inundation model" (e.g. Hunter et al. 2007). The model equations are derived based on the following mass balance equation (1) and momentum equation (2) for gradually varied unsteady flow.

$$\frac{\partial h}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=r-f \quad (1)$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial uq_x}{\partial x}+\frac{\partial vq_x}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho_w} \quad (2)$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial uq_y}{\partial x}+\frac{\partial vq_y}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{\tau_y}{\rho_w} \quad (3)$$

where h is the height of water from the local surface, q_x and q_y are the unit width discharges in x and y directions, u and v are the flow velocities in x and y directions, r is the rainfall intensity, f is the infiltration rate, H is the height of water from the datum, ρ_w is the density of water, g is the gravitational acceleration, and τ_x and τ_y are the shear stresses in x and y directions. The second terms of the right side of (2) and (3) are calculated with the Manning’s equation.

$$\frac{\tau_x}{\rho_w}=\frac{gn^2u\sqrt{u^2+v^2}}{h^{1/3}} \quad (4)$$

$$\frac{\tau_y}{\rho_w}=\frac{gn^2v\sqrt{u^2+v^2}}{h^{1/3}} \quad (5)$$

where n is the Manning’s roughness parameter.

Under the diffusion wave approximation, inertia terms (the left side terms of (2) and (3)) are neglected. Moreover, by separating x and y directions (i.e. ignoring v and u terms in equations (2) and (3) respectively), the following equations are derived:

$$q_x=-\frac{1}{n}h^{5/3}\sqrt{\left|\frac{\partial H}{\partial x}\right|}\operatorname{sgn}\left(\frac{\partial H}{\partial x}\right) \quad (6)$$

$$q_y=-\frac{1}{n}h^{5/3}\sqrt{\left|\frac{\partial H}{\partial y}\right|}\operatorname{sgn}\left(\frac{\partial H}{\partial y}\right) \quad (7)$$

where sgn is the signum function.

The RRI model spatially discretizes mass balance equation (1) as follows:

$$\frac{dh^{i,j}}{dt}+\frac{q_x^{i,j-1}-q_x^{i,j}}{\Delta x}+\frac{q_y^{i-1,j}-q_y^{i,j}}{\Delta y}=r^{i,j}-f^{i,j} \quad (8)$$

where $q_x^{i,j}$, $q_y^{i,j}$ are x and y direction discharges from a grid cell at (i, j).

By combining the equations of (6), (7) and (8), water depths and discharges are calculated at each grid cell for each time step. One important difference between the RRI model and other inundation models is that the former uses different forms of the discharge-hydraulic gradient relationship, so that it can simulate both surface and subsurface flows with the same algorithm. The RRI model replaces the equations (6) and (7) with the following equations of (9) and (10), which were originally conceptualized by Ishihara and Takasao (1962) and formulated with a single variable by Takasao and Shiiba (1976, 1988) based on kinematic wave approximations. The first equations in (9) and (10) ($h \le d$) describe the saturated subsurface flow based on the Darcy law, while the second equations ($d_a \le h$) describe the combination of the saturated subsurface flow and the surface flow. Note that for the kinematic wave model, the hydraulic gradient is assumed to be equal to the topographic slope, whereas the RRI model assumes the water surface slope as the hydraulic gradient.

$$q_x=\begin{cases}-k_a h\dfrac{\partial H}{\partial x}, & (h\le d)\\ -\dfrac{1}{n}(h-d_a)^{5/3}\sqrt{\left|\dfrac{\partial H}{\partial x}\right|}\operatorname{sgn}\left(\dfrac{\partial H}{\partial x}\right)-k_a h\dfrac{\partial H}{\partial x}, & (d_a<h)\end{cases} \quad (9)$$

$$q_y=\begin{cases}-k_a h\dfrac{\partial H}{\partial y}, & (h\le d)\\ -\dfrac{1}{n}(h-d_a)^{5/3}\sqrt{\left|\dfrac{\partial H}{\partial y}\right|}\operatorname{sgn}\left(\dfrac{\partial H}{\partial y}\right)-k_a h\dfrac{\partial H}{\partial y}, & (d_a<h)\end{cases} \quad (10)$$

where k_a is the lateral saturated hydraulic conductivity and d_a is the soil depth times the effective porosity.

Equations (11) and (12) can be also used to simulate the effect of unsaturated, saturated subsurface flow and surface flow with the single variable of h (Tachikawa et al. 2004, Sayama and McDonnell 2009 for English readers).

$$q_x=\begin{cases}-k_m d_m\left(\dfrac{h}{d_m}\right)^{\beta}\dfrac{\partial H}{\partial x}, & (h\le d_m)\\ -k_a(h-d_m)\dfrac{\partial H}{\partial x}-k_m d_m\dfrac{\partial H}{\partial x}, & (d_m<h\le d_a)\\ -\dfrac{1}{n}(h-d_a)^{5/3}\sqrt{\left|\dfrac{\partial H}{\partial x}\right|}\operatorname{sgn}\left(\dfrac{\partial H}{\partial x}\right)-k_a(h-d_m)\dfrac{\partial H}{\partial x}-k_m d_m\dfrac{\partial H}{\partial x}, & (d_a<h)\end{cases} \quad (11)$$

$$q_y = \begin{cases} -k_m d_m \left(\dfrac{h}{d_m}\right)^{\beta} \dfrac{\partial H}{\partial y}, & (h \le d_m) \\ -k_a (h - d_m) \dfrac{\partial H}{\partial y} - k_m d_m \dfrac{\partial H}{\partial y}, & (d_m < h \le d_a) \\ -\dfrac{1}{n} (h - d_a)^{5/3} \sqrt{\left|\dfrac{\partial H}{\partial y}\right|} \operatorname{sgn}\left(\dfrac{\partial H}{\partial y}\right) - k_a (h - d_m) \dfrac{\partial H}{\partial y} - k_m d_m \dfrac{\partial H}{\partial y}, & (d_a < h) \end{cases} \quad (12)$$

Note that to assure the continuity of the discharge change when $h = d_m$, the lateral hydraulic conductivity in unsaturated zone (k_m) can be computed by $k_m = k_a / \beta$, so that k_m is no longer the model parameter.

These stage-discharge relationship equations were originally developed to be applied to humid forest areas with a high permeable soil layer, where a lateral subsurface flow is the dominant runoff generation mechanism. On the other hand, for relatively flat areas, the vertical infiltration process during the first period of rainfall has more impact on large-scale flooding; therefore, the vertical infiltration can be treated as loss for event-based simulation. Here we calculate infiltration loss f with the Green-Ampt infiltration model (Raws et al., 1992).

$$f = k_v \left[1 + \frac{(\phi - \theta_i) S_f}{F} \right] \quad (13)$$

where k_v is the vertical saturated hydraulic conductivity, ϕ is the soil porosity, θ_i is the initial water volume content, S_f is the suction at the vertical wetting front and F is the cumulative infiltration depth.

Typically for mountainous areas where lateral subsurface flow and saturated excess overland flow dominate, the equations (9) and (10) (or (11) and (12)) can be used with setting f equals to be zero. (Note that the equations (9) and (10) (or (11) and (12)) implicitly assume that the vertical infiltration rate within the soil is infinity.) On the other hand, for plain areas where infiltration excess overland flow dominates, the surface flow equations (6) and (7) can be used with the consideration of vertical infiltration by equation (13). If the vertical infiltration f is set to be non-zero and the lateral subsurface equations are used instead of the surface flow equation, the lateral subsurface water is infiltrated to bedrock by the rate of f.

As one can see from the equations, the parameter values of k_a, km and k_v decide which equations to be used; i.e. (6) and (7) are used when k_a and k_m are zero, (9) and (10) are used when k_m is zero, and (13) is inactivated when k_v is zero.

1.3 One-dimensional River Routing Model

A one-dimensional diffusive wave model is applied to river grid cells. The geometry is assumed to be rectangle, whose shapes are defined by width W, depth D and embankment height H_e. When detailed geometry information is not available, the width and depth are approximated by the following function of upstream contributing area A [km^2].

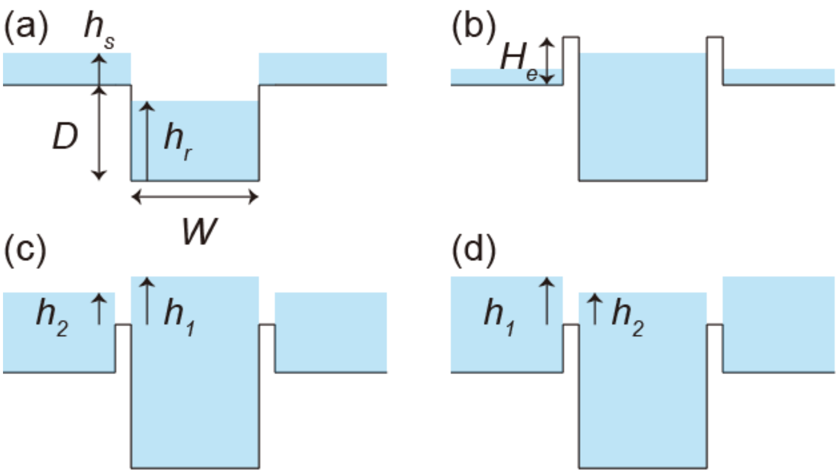
$$W = C_W A^{S_W} \quad (14)$$

$$D = C_D A^{S_D} \quad (15)$$

where C_W, S_W, C_D and S_D are geometry parameters. Here the units of W and D are meters.

1.4 River and Slope Water Exchange

Water exchange between a slope grid cell and an overlying river grid cell is calculated at each time step depending on the relationship among the levels of slope water, river water, levee crown and ground. The figure below shows four different conditions. For each condition, different overtopping formulae are applied to calculate the unit length discharge from slope to river (q_{sr}) or from river to slope (q_{rs}), which are then multiplied by the length of the river vector at each grid cell to calculate the total exchange flow rate (Iwasa and Inoue, 1982).



1) When the river water level is lower than the ground level, q_{sr} is calculated by the following step fall formula.

$$q_{sr} = \mu_1 h_s \sqrt{g h_s} \quad (16)$$

where μ_1 is the constant coefficient (=(2/3)$^{3/2}$), and h_s is the water depth on a slope cell. As far as the river water level is lower than the ground level, the same equation is used even for the case with levees so that the slope water can flow into the river.

2) When the river water level is higher than the ground level and both the river and slope water levels are lower than the levee height, no water exchange is assumed between the slope and river.

3) When the river water level is higher than the levee crown and the slope water level, the following formula is used to calculate overtopping flow q_{rs} from river to slope.

$$q_{rs} = \begin{cases} \mu_2 h_1 \sqrt{2gh_1} & h_2 / h_1 \le 2/3 \\ \mu_3 h_2 \sqrt{2g(h_1 - h_2)} & h_2 / h_1 > 2/3 \end{cases} \quad (17)$$

where μ_2 and μ_3 are the constant coefficients (=0.35, 0.91), and h_1 is the difference between the river water level and the levee crown.

4) When the slope water level is higher than the levee height and the river water level, the same formula as (17) is used to calculate overtopping flow q_{sr} from slope to river. In this case, h_1 is the elevation difference between the slope and the river, and h_2 is the elevation difference between the river and the levee crown.

1.5 Numerical Scheme

To solve equations (8), (9) and (10), the fifth-order Runge-Kutta method with adaptive time-step control is applied. This method solves an ordinary differential equation by the general fifth-order Runge-Kutta formula and estimates its error by an embedded forth-order formula to control the time-step (Cash and Karp 1990, Press et al 1992).

The general form of the fifth-order Runge-Kutta formula is

$$\begin{aligned} k_1 &= \Delta t f(t, h_t) \\ k_2 &= \Delta t f(t + a_2 \Delta t, h_t + b_{21} k_1) \\ &\cdots \\ k_6 &= \Delta t f(t + a_6 \Delta t, h_t + b_{61} k_1 + \cdots b_{65} k_5) \\ h_{t+1} &= h_t + c_1 k_1 + c_2 k_2 + c_3 k_3 + c_4 k_4 + c_5 k_5 + c_6 k_6 + O(\Delta t^6) \end{aligned} \quad (18)$$

while the embedded forth-order formula (Cash and Karp 1990) is

$$h^*_{t+1} = h_t + c^*_1 k_1 + c^*_2 k_2 + c^*_3 k_3 + c^*_4 k_4 + c^*_5 k_5 + c^*_6 k_6 + O(\Delta_t^5) \quad (19)$$

By subtracting h_{t+1} minus h^*_{t+1}, the error can be estimated by using k_1 to k_6 as follows,

$$\delta \equiv h_{t+1} - h_t^* = \sum_{i=1}^{6} \left(c_i - c_i^*\right) k_i \quad (20)$$

The constant values (a_i, b_{ij}, c_i, c_i^*) used in this study are the ones introduced by Cash and Karp (1990). If δ exceeds a desired accuracy δ_d, h_{t+1} is recalculated with a smaller time step (Δt_{post}).

$$\Delta t_{post} = \max\left(0.9\Delta t \left| \frac{\delta_d}{\delta} \right|^{0.25}, 0.5\Delta t \right) \quad (21)$$

As described above, the RRI model calculates slopes, rivers and slope-river interactions. Model users specify the time step for slope-river interaction Δt, which is also used as an initial time step for slope calculations. Since river calculations usually require smaller time steps because of higher water velocities and depths, the model allows river calculations to proceed independently with different time steps until the next river-slope calculation time step. The initial time step for river calculation (Δt_r) can be also specified by model users as the common divisor of Δt. In this study, $\delta_d = 0.01$, $\Delta t = 600$ sec. and $\Delta t_r = 60$ sec. were used.

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2. Getting Started

There are essentially five steps to conduct RRI Model simulation.

1. Preparing topography data (Section 3)
2. Preparing input rainfall data (Section 4)
3. Preparing model condition files with parameter settings (Section 5)
4. Executing RRI Model. (Section 6)
5. Plotting output data (Section 7)

Among the five steps, only the essence of step 4 and 5 are described here with sample data of the Solo River Basin (in 30 sec resolution) in Indonesia.

2.1 Compile

Unzip "RRI_1.3.zip" and save it on a working directory (e.g. C:/).

Open CUI environment where you can compile Fortran programs

(For Intel Fortran Users on Windows)
Start → Program → Intel(R) Software Development Tools → Intel(R) Fortran Compiler **
→ Fortran Build Environment for Applications running on …

Move current directory to "/RRI/Model/", then type "make.bat" and enter to create "0_rri.exe". (Command "*cd directory_name*" is used to enter the directory, "cd ../" is used to move up one directory, and "dir" is used to list all files and directories in the current directory. To move D directory, just type "D:" and enter)

Also type "makePostProsess.bat" and enter to create "calcHydro.exe" and "calcPeak.exe", which are used for post processing.

Make sure if "0_rri.exe", "calcHydro.exe" and "calcPeak.exe" are newly created.

2.2 Run RRI Model

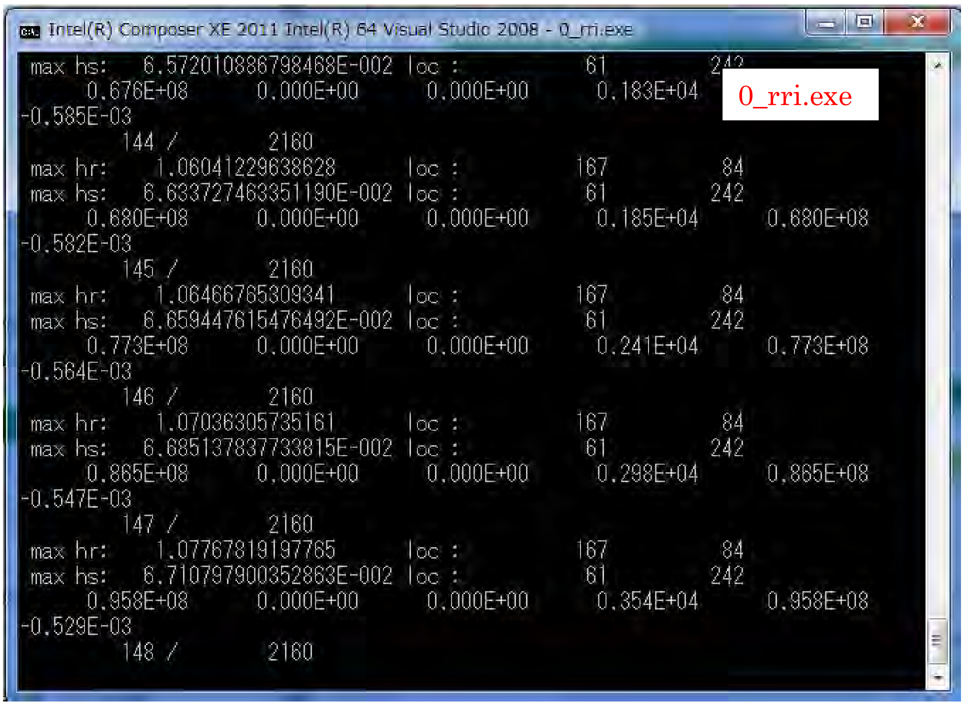
Look at "RRI_Input.txt", which is the control file of RRI Model. You can edit the control file to change the simulation settings including input files and parameters.

```
RRI_Input_Format_Ver1_3

./infile/solo30s/rain_solo_30s_gauge.dat
./infile/solo30s/adem2_30s_solo.txt
./infile/solo30s/acc_30s_solo.txt
./infile/solo30s/adir_30s_solo.txt

0                  # utm(1) or latlon(0)
1                  # 4-direction (0), 8-direction(1)
360                # lasth
600                # dt
```

RRI_Input.txt

For example, L3 specifies the path to an input rainfall file and L4 – L6 specify the paths to input topography files (dem, acc, and dir). See Section 4 for more details on the RRI_Input.txt file.

Execute "0_rri.exe" to run RRI Model.



Confirm the output files are successfully created inside the directory of "RRI/Model/out". Note that "hr_000001.out" represents the spatial distribution of river water depths in [m] at the output time step 1. "hr_000001.out" and "qr_000001.out" represent those of slope water depths in [m] and river discharge in [m^3/s], respectively.

2.3 Post Analysis

2.3.1 Visualize Inundation Depth (./out/hs_***.out) with GNUPLOT

Look at "RRI/Model/hs.plt", which is a GNUPLOT script file to convert from the simulation outputs (e.g. ./out/hs_***.out) to gif files to visualize inundation depth distributions.

hs_plt.txt

```
reset

set terminal gif medium size 672, 408 crop

set pm3d map
set palette defined (0.0 "gray", 1.5 "blue", 3 "green")

set xrange [0:]
set yrange [:] reverse
set zrange [0:] reverse

#set xrange [180:200]
#set yrange [435:455] reverse

set cbrange[0.:3]
set zrange[0.0:]

set output "./hs/hs_000001.gif"
splot "./out/hs_000001.out" matrix t "000001 / 000096"

set output "./hs/hs_000002.gif"
splot "./out/hs_000002.out" matrix t "000002 / 000096"

set output "./hs/hs_000003.gif"
splot "./out/hs_000003.out" matrix t "000003 / 000096"
```

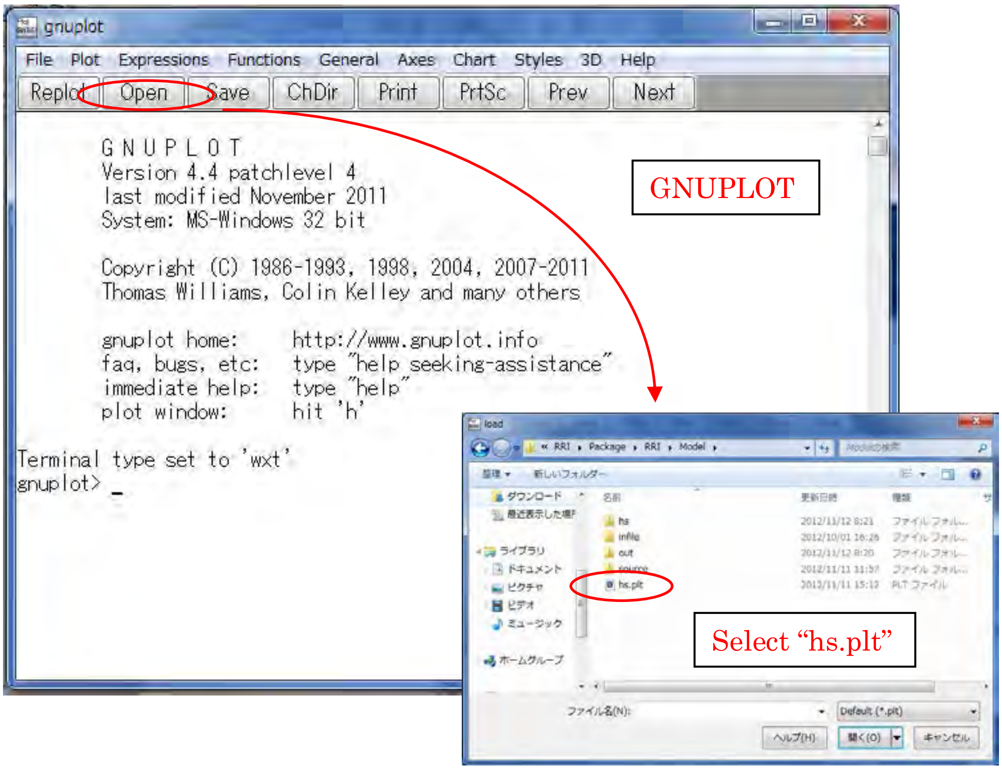
From RRI output (hs_***.out) to gif

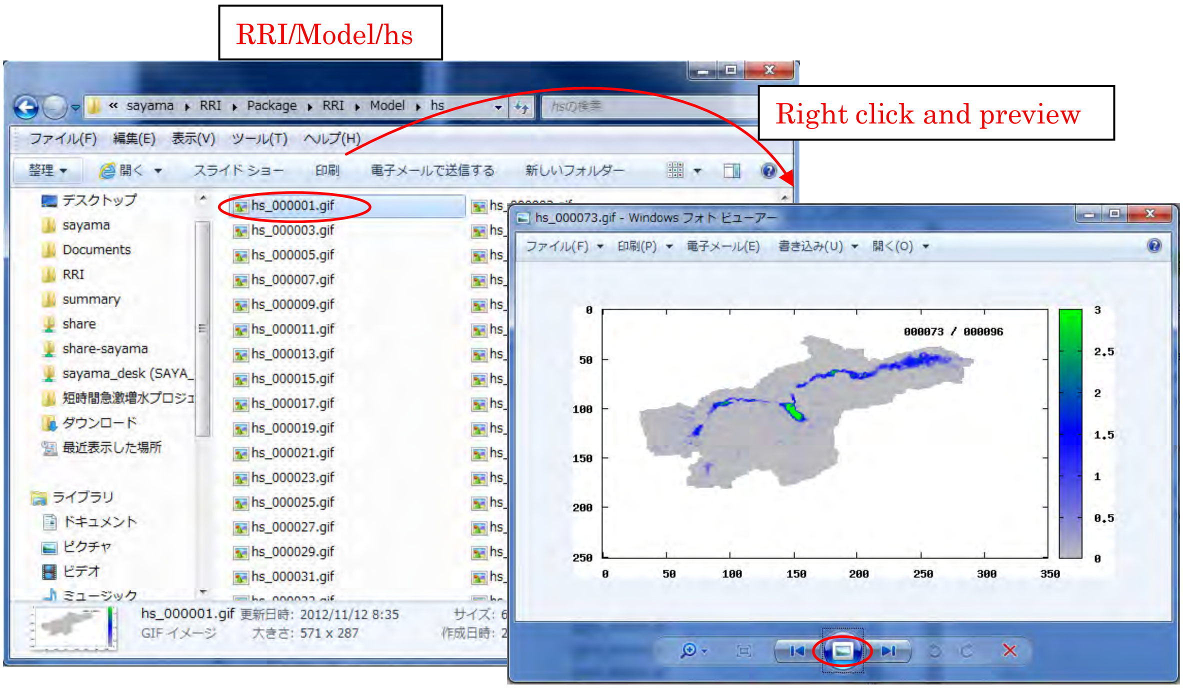
Start GNUPLOT program by clicking "RRI/etc/gnuplot/binary/wgnuplot.exe"

If fonts are invisible, right click and "Choose Font…" to enlarge the fonts (e.g. 14 points) and ok. Then right click again to select "update … wgnuplot.ini" to keep the selected fonts as default.

Select "Open" on GNUPLOT Tab and open "/RRI/Model/hs.plt", which is a script file to create gif files from the RRI output (see above figure).

Look at “RRI/Model/hs” directory, where gif files are newly created. Check the created gif files by preview.





2.3.2 Compute hydrograph

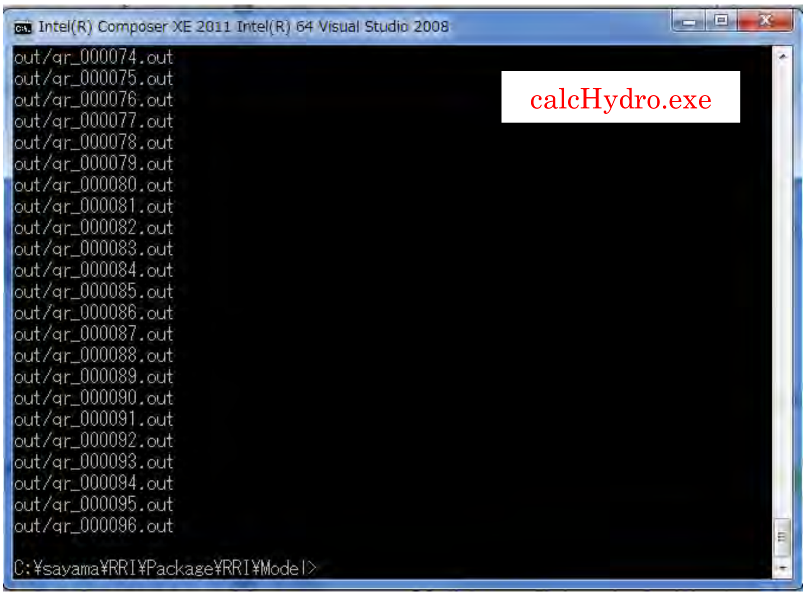
Look at “RRI/Model/calcHydro.txt” (see more details “RRI/etc/calcHydro/00_readme.txt”)

L1 : [In] location file (e.g. ./infile/solo30s/location_30s_solo.txt)

L2 : [In] RRI output file (e.g. ./out/qr_***.txt)

L3 : [Out] hydrograph file (e.g. ./infile/solo30s/disc_Cepu.txt)

Execute "calcHydro.exe".



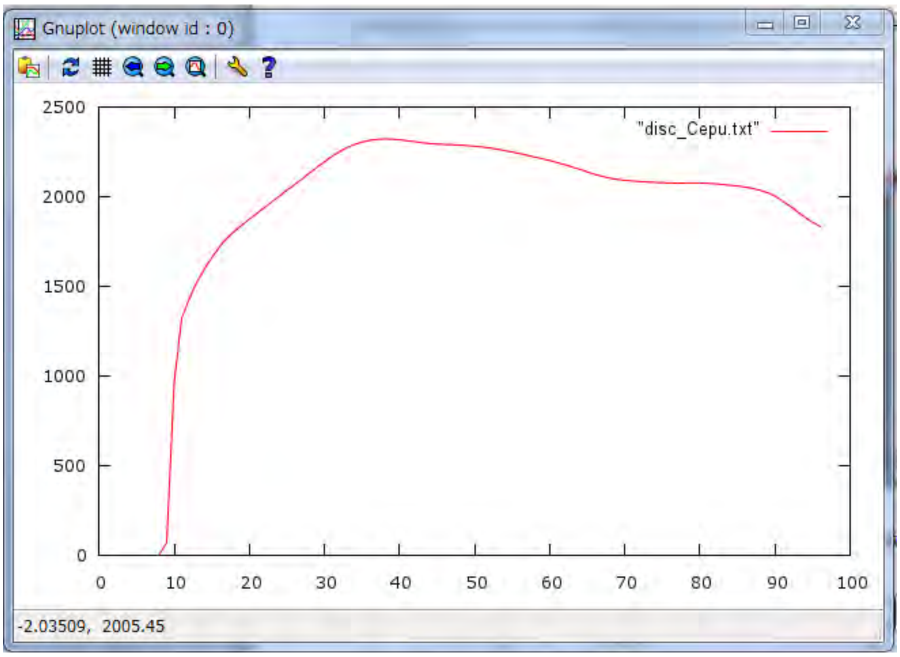
A hydrograph file named "disc_Cepu.txt" is created inside "RRI/Model/infile/solo30s".

./infile/solo30s/disc_cepu.txt

1	0.00789
2	0.04591
3	0.08256
4	0.10557
5	0.12529
6	0.14543
7	0.24838
8	0.56375
9	69.88281
10	967.36834
11	1322.37727
12	1429.53330
13	1518.85970
…..	……

Visualize the created hydrograph file (e.g. "./infile/solo30s/disc_Cepu.txt") by GNUPLOT.

From GNUPLOT screen, open and select "hydrograph.plt", which is a GNUPLOT script file to plot hydrograph from the "disc_Cepu.txt".



2.3.3 Compute and visualize peak inundation depths

Look at "RRI/Model/calcPeak.txt" (see more details "RRI/etc/calcPeak/00_readme.txt") and edit the file if necessary.

L1 : [in] dem file

L2 : [in] output file (e.g. ./out/hs_***.out)

L3 : [in] the number of output files

L4 : [out] output peak inundation depth file (e.g. ./infile/solo30s/hpeak_30s_solo.txt)

Execute "calcPeak.exe". Then the file "hpeak_30s_solo.txt" is created under /infile/solo30s/

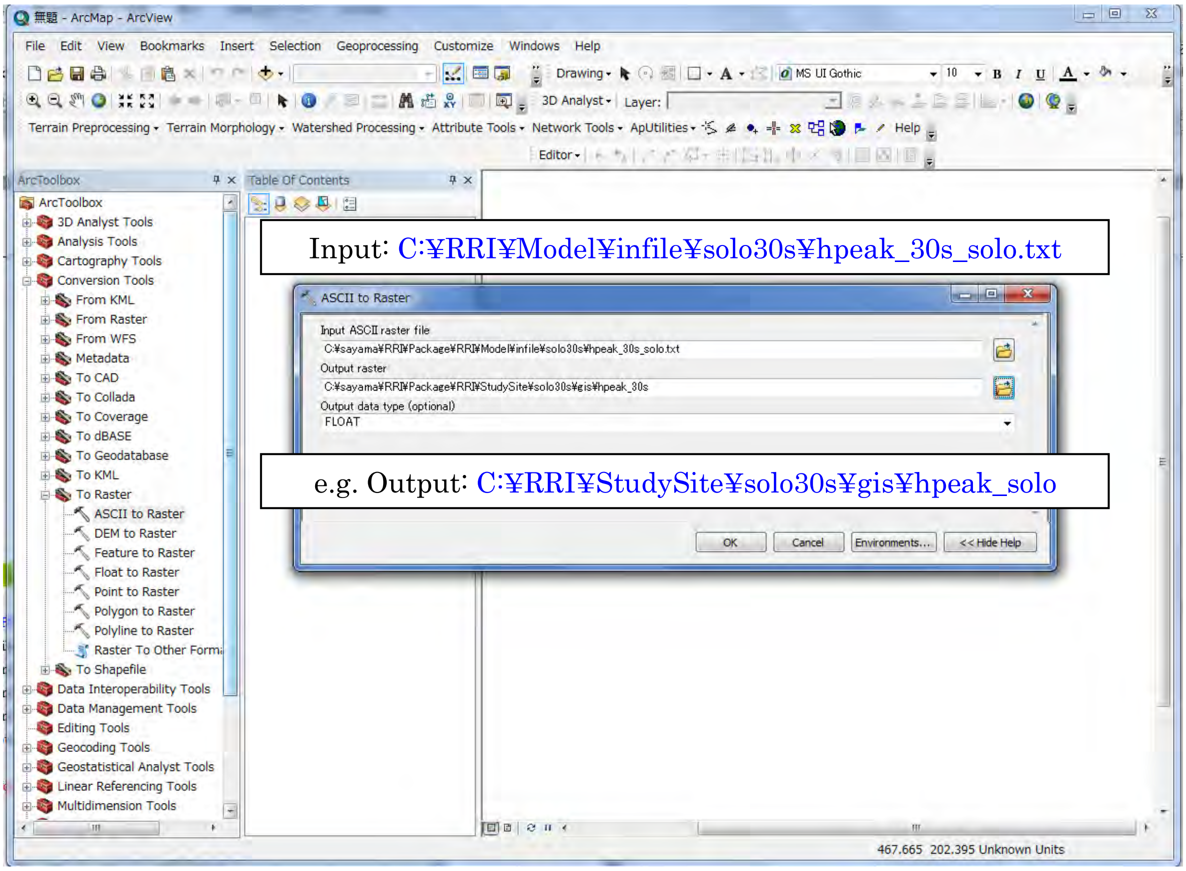
hpeak_30s_solo.txt

```
ncols          336
nrows           204
xllcorner      110.2
yllcorner      -8.3
cellsize       0.00833333333333
NODATA_value   -9999
 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

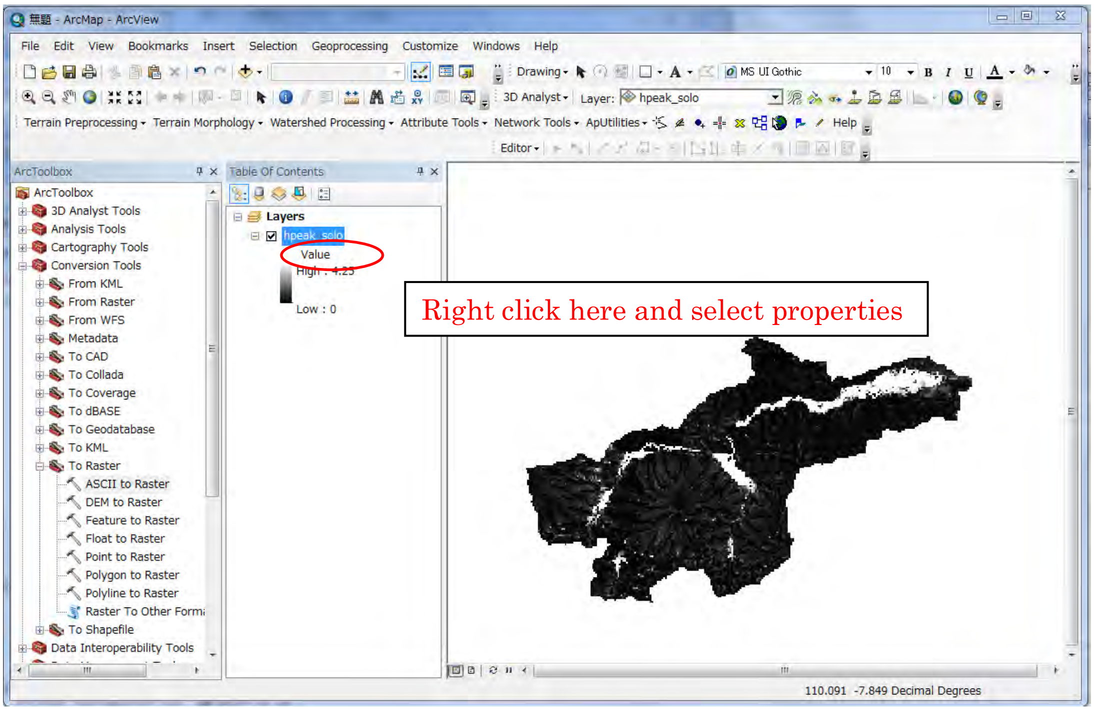
Visualize the created "hpeak_30s_solo.txt" on ArcGIS by converting it from ASCII to Raster.

1) Start ArcGIS

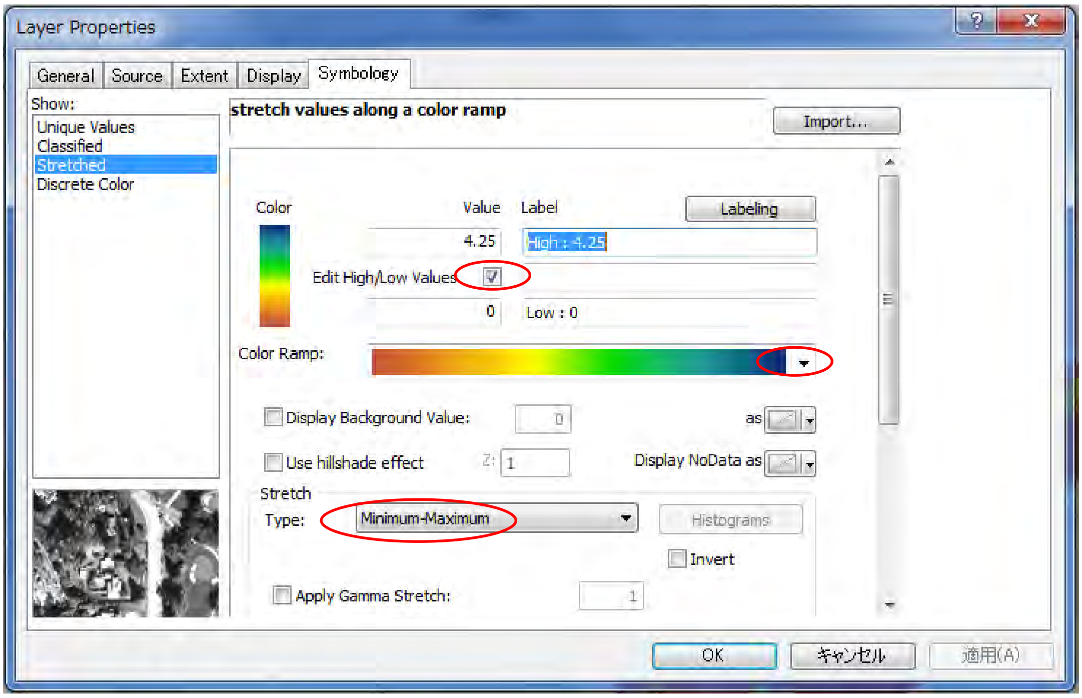
2) From ArcToolbox → [Conversion Tools] → [To Raster] → [ASCII to Raster]



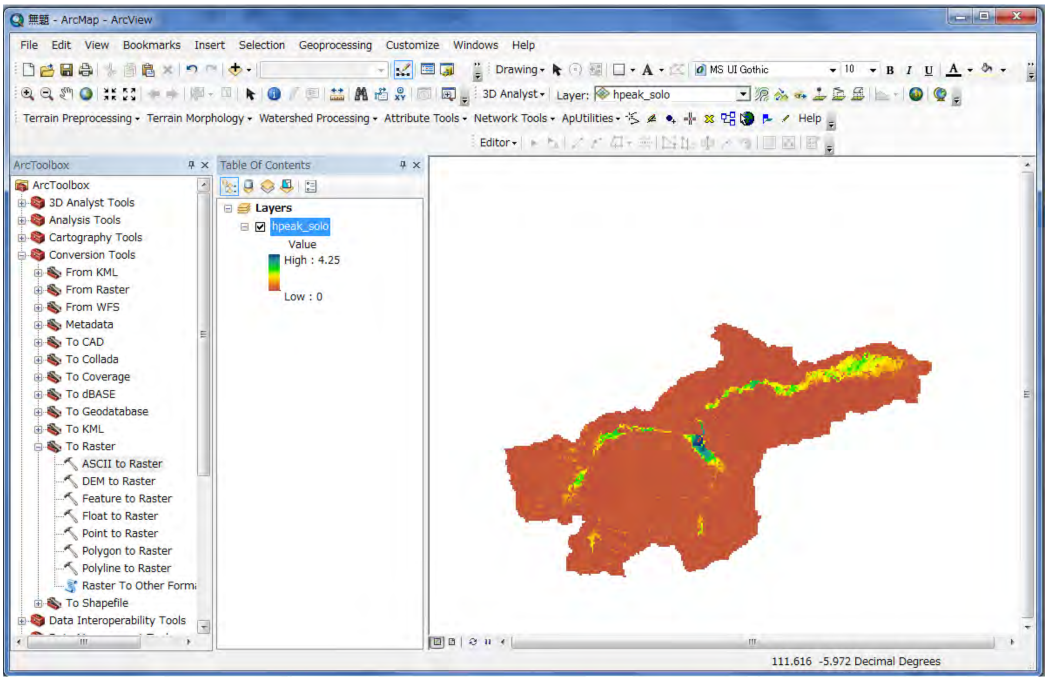
3) For the input data, select "hpeak_30s_solo.txt". For the output raster, a user may use "RRI/StudySite/solo30s/gis/hpeak_solo".



4) Right click “hpeak_30s” and select properties to change the layer color setting.



5) On the layer property, change the stretch type to “Minimum-Maximum” and change Color Ramp if necessary. By checking “Edit High/Low Values”, you can change the max and min value range of the stretching.

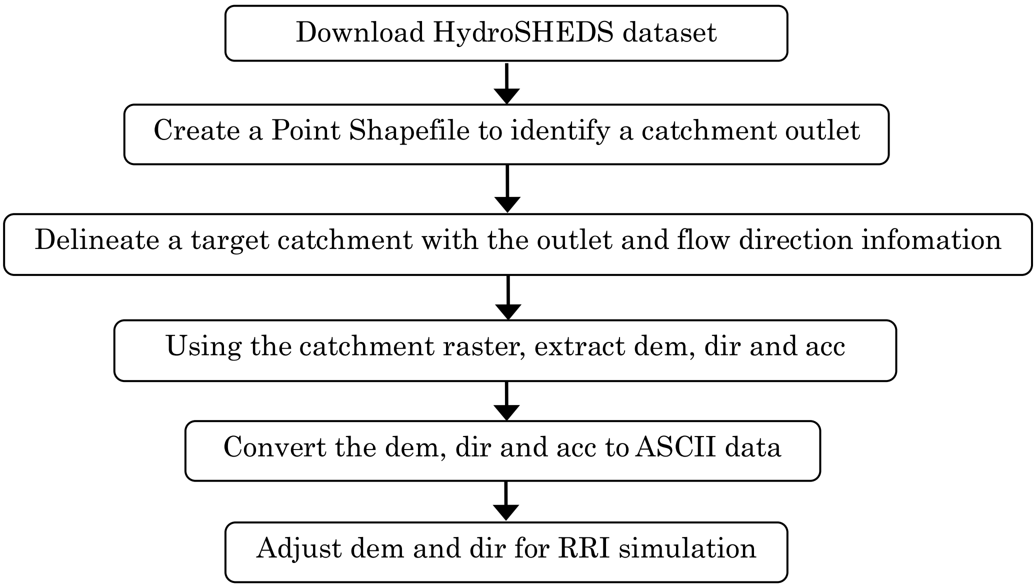


3. Preparing Input Topography Data

This section shows the method to prepare topography data input to the RRI Model. The topography data can be prepared by a user or downloaded from the website of USGS HydroSHEDS, which is a global scale dataset offered by the United States Geological Survey (USGS). The dataset includes elevation, flow direction and flow accumulation.

From the downloaded topographic dataset, a user must clip out the target river basin and save them as ESRI/ASCII format files. Then using a program included in RRI Model package, one adjusts the original DEM and flow direction data to be suitable for the RRI simulation. The following chart shows the procedure descried in this section. In the previous section, the 30 second resolution of the Solo River Basin data was used, whereas this section presents how to prepare the topographic data in 15 second.

The flow of the procedure is as follows.



3.1 Downloading HydroSHEDS Data

The following three types of topography data must be downloaded from HydroSHEDS website for RRI simulation.

1) Elevation data

3 arc-second (about 90 m), 15 arc-second (about 500 m), and 30 arc-second (about 1,000 m) are available.

2) Flow direction data

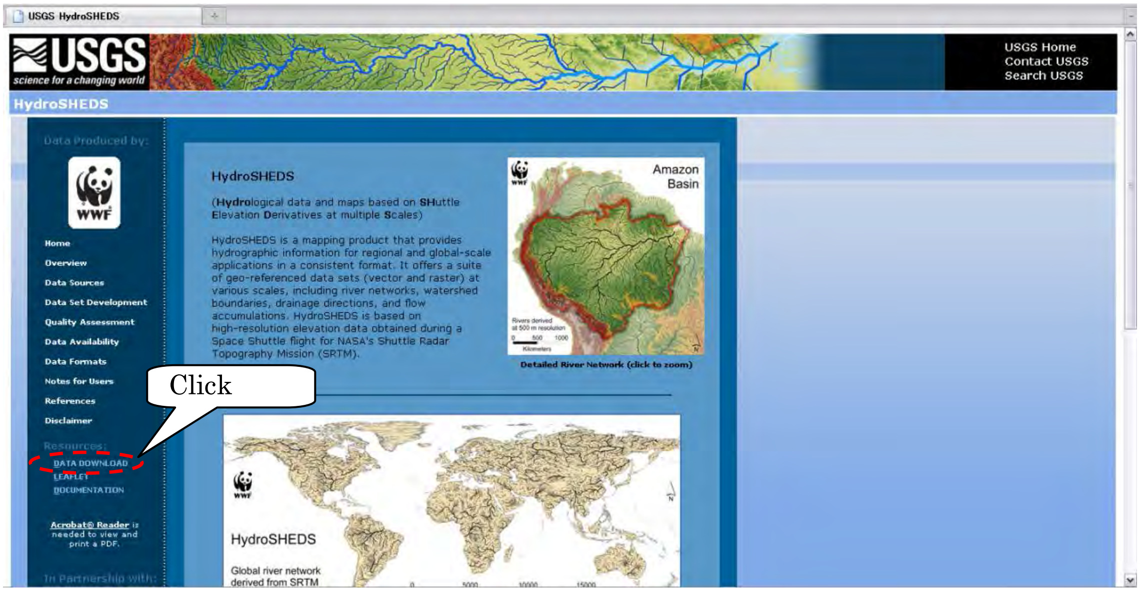
3 arc-second, 15 arc-second, and 30 arc-second are available.

3) Flow accumulation data

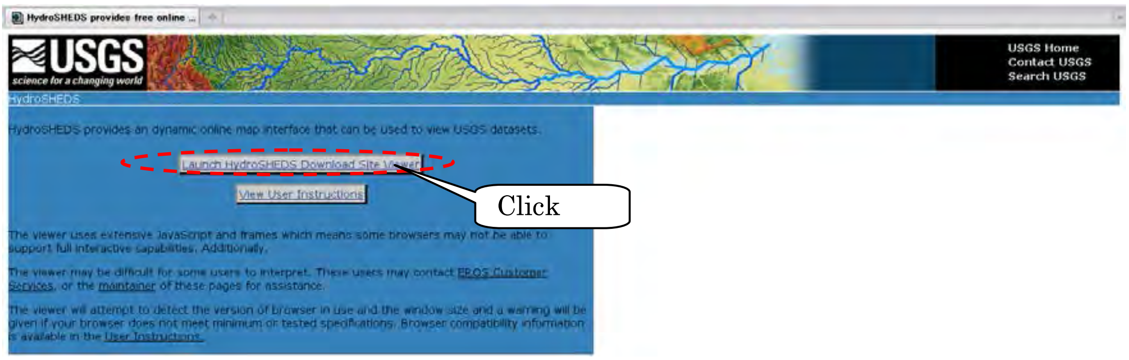
Only 15 arc-second and 30 arc-second are available. For 3 arc-second resolution, a user must prepare a flow accumulation by using a GIS function [Spatial Analyst] → [Hydrology] → [Flow Accumulation].

※ For detailed specifications of HydroSHEDS, refer to HydroSHEDS Technical Documentation packaged with the downloaded data.

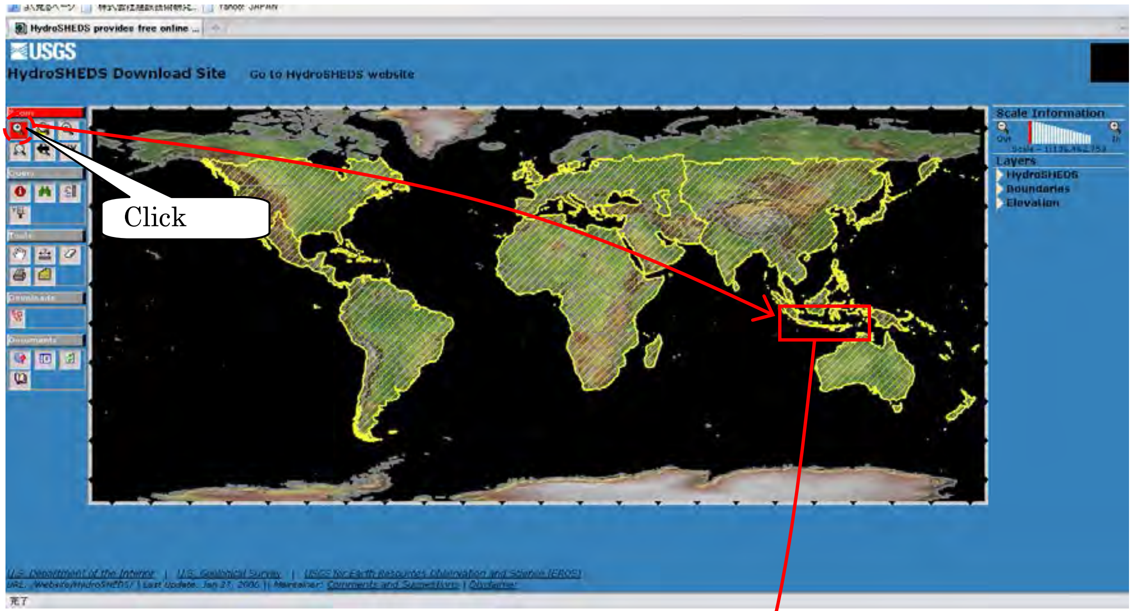
① Access USGS HydroSHEDS website （http://hydrosheds.cr.usgs.gov/index.php） from a web browser and then select and click the DATADOWNLOAD button on the lower left.



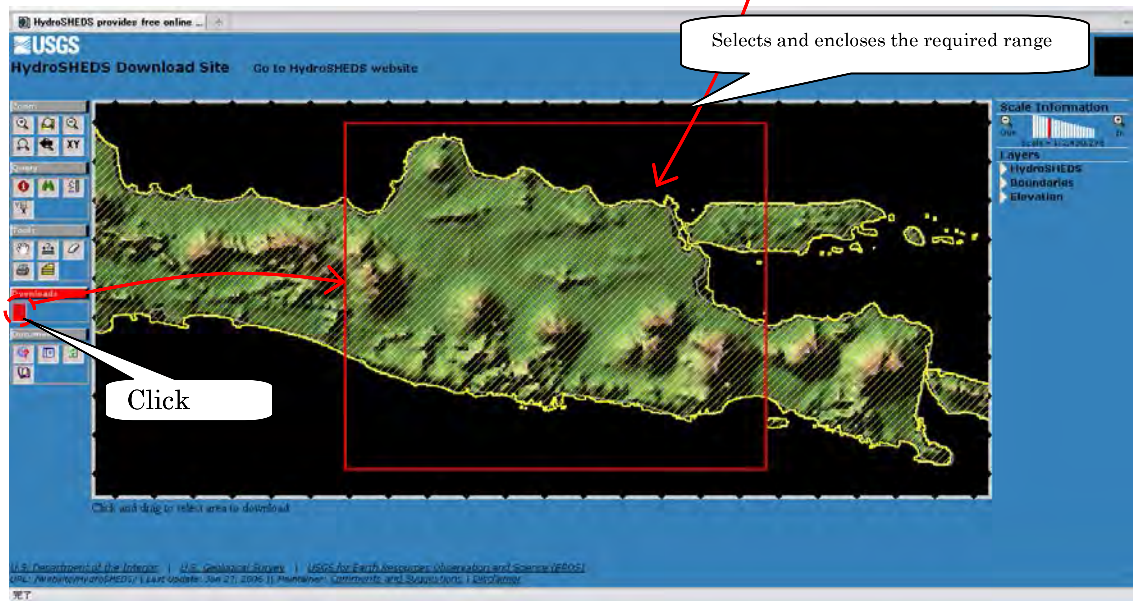
② Select and click the Launch HydroSHEDS Download Site Viewer button.



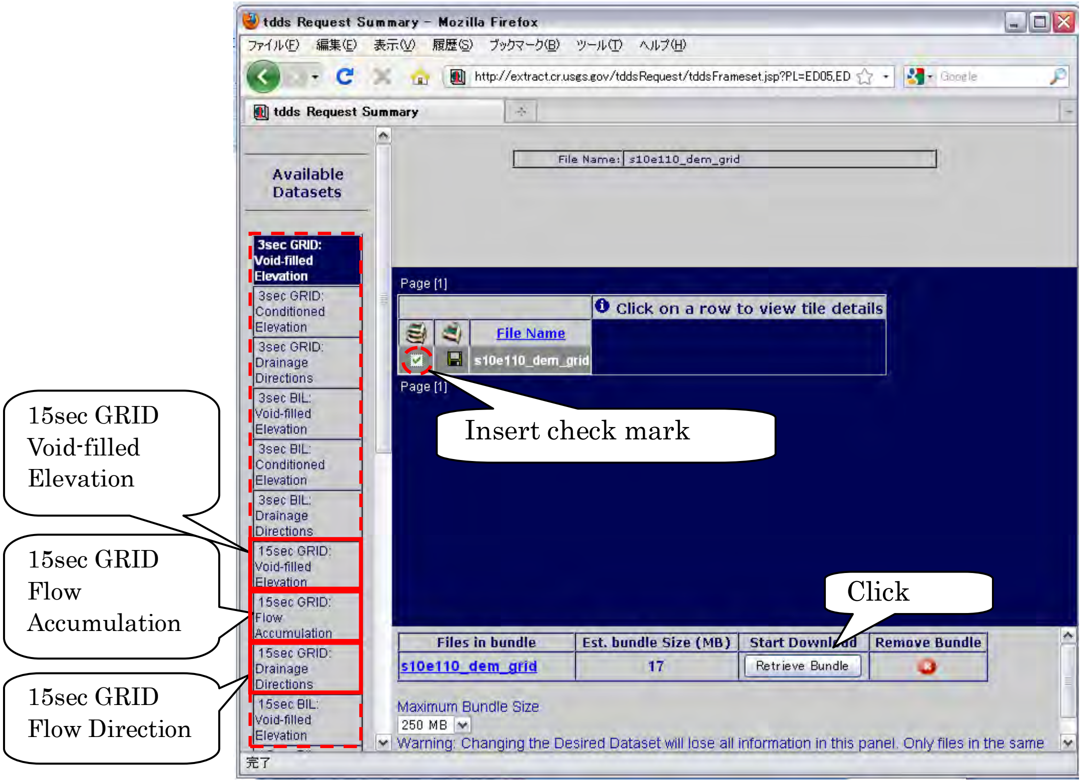
③ Select the enlarge button in the Zoom category and select the scope of the range you wish to download.



④ The selected range expands then click a button in the downloads category.



⑤ Insert a check mark into File Name and select Retrieve Bundle in Start Download.



NOTE: Do not choose “Conditioned Elevation”. Select “Void-filled Elevation”.

Then the download preparation window appears, then save it on your computer.

3.2 Delineating HydroSHEDS Data using ArcGIS

① Unzip the three types of topography data you downloaded.

Data is placed in folders as follows.

Folder: 42624602・・・Flow direction data

Folder: 56426042・・・Flow accumulation data

Folder: 86426042・・・Elevation data

※Folder naming rule

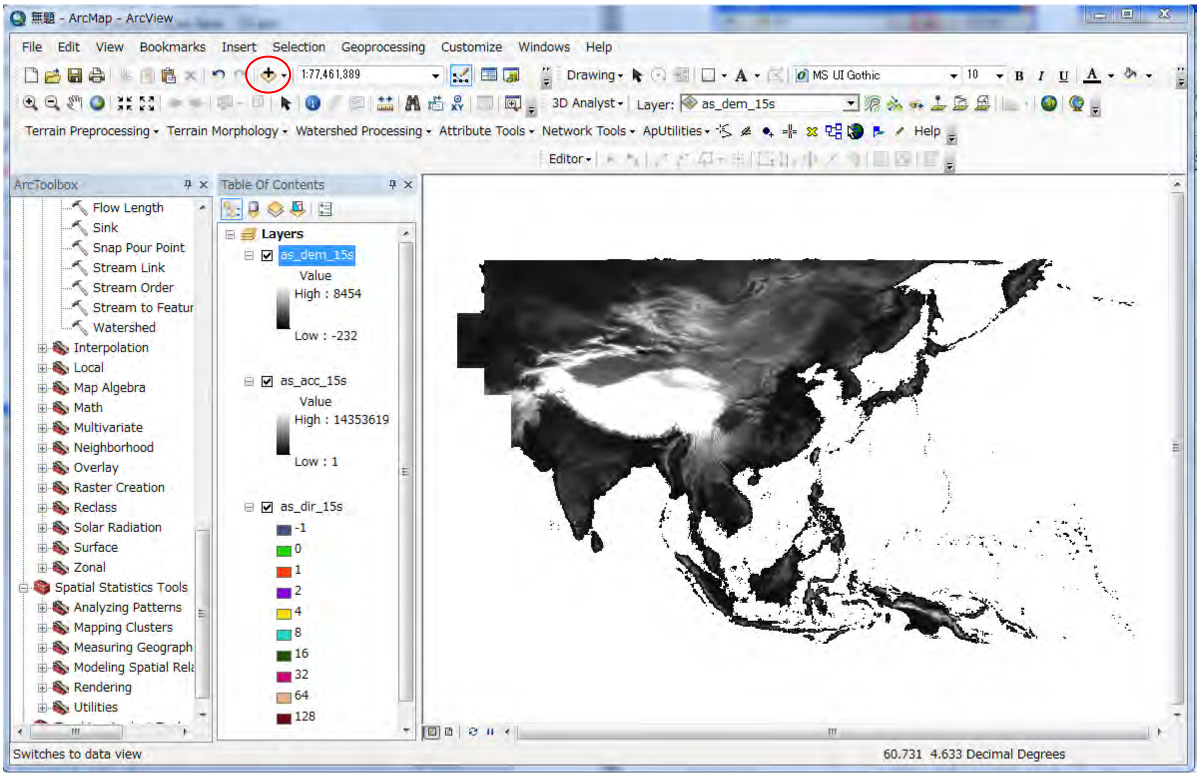
“Continental range” _ ”Data type” _ “resolution”

e.g.) as_acc_15s → Asia catchment area data 15 sec

as_dem_15s → Asia digital elevation data 15 sec

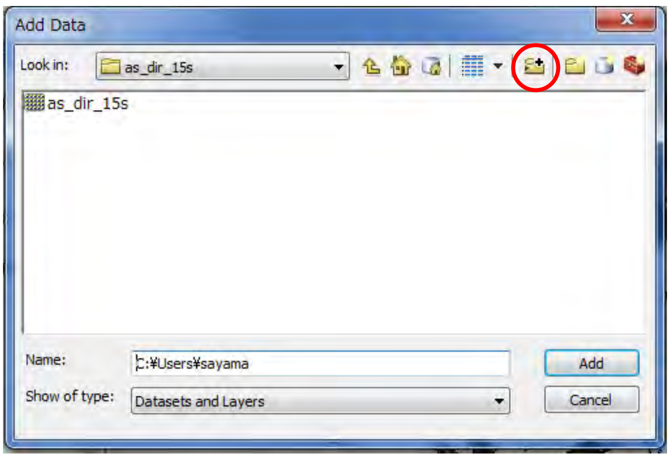
as_dir_15s → Asia flow direction data 15 sec

② Start ArcMap, and read in the unzipped files by selecting [File]>[Add Data]. (Or use icon of “Add Data” on the standard tool bar). Perform the same operation for all the three types (dem, dir, acc) of topography data.

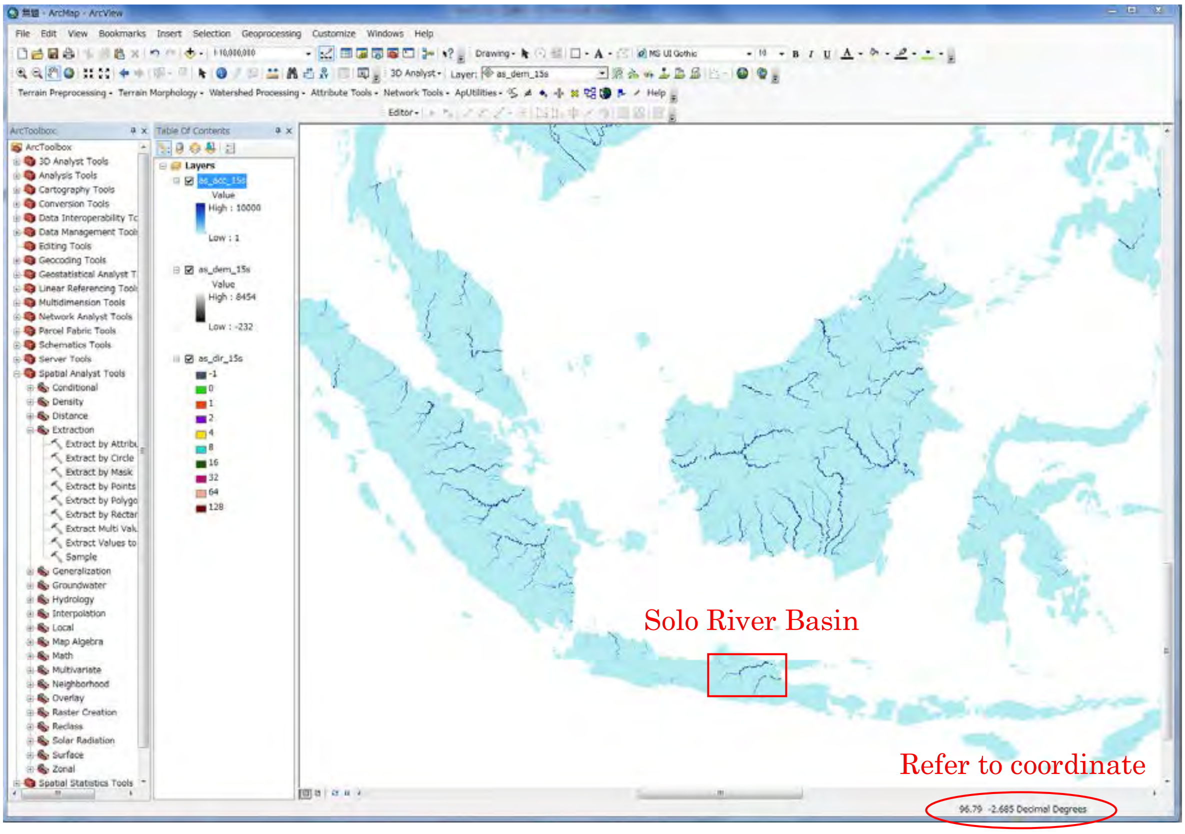


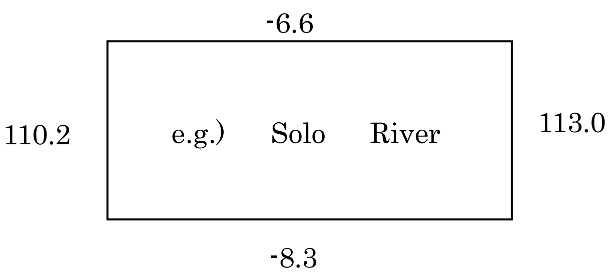
※Selecting the folder to connect

If the folder you need to connect is not displayed in the window, click “Connect to Folder” to connect to the working folder.

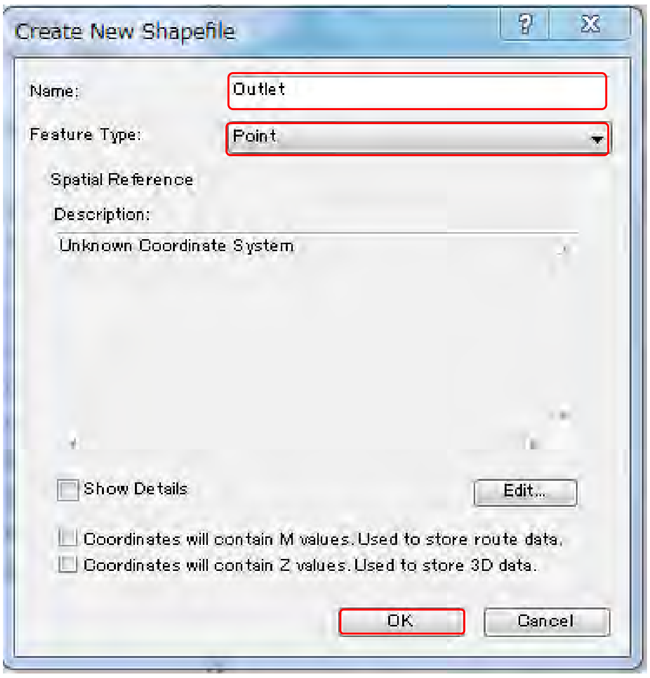


③ Display the flow accumulation data (i.e. as_acc_15s) on top screen (change the color range to show river network clearly). Then find out your target river and decide the rectangular range used for the simulation.



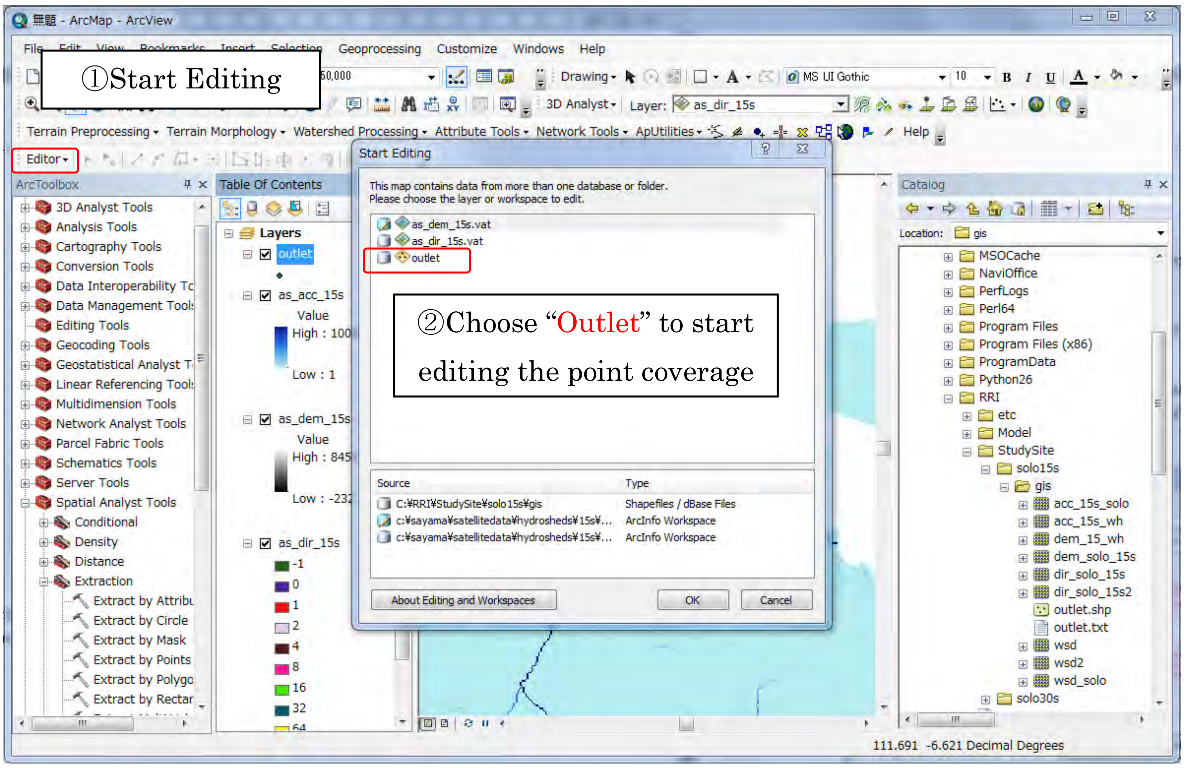


④ Show arc catalog (from the main menu, [Windows] → [Catalog]).
On the arc catalog, "Folder Connections" to a working folder (e.g. /RRI/StudySite/Solo15s/gis/) and right click to choose New → Shapefile to create a point Shapefile (e.g. Outlet).



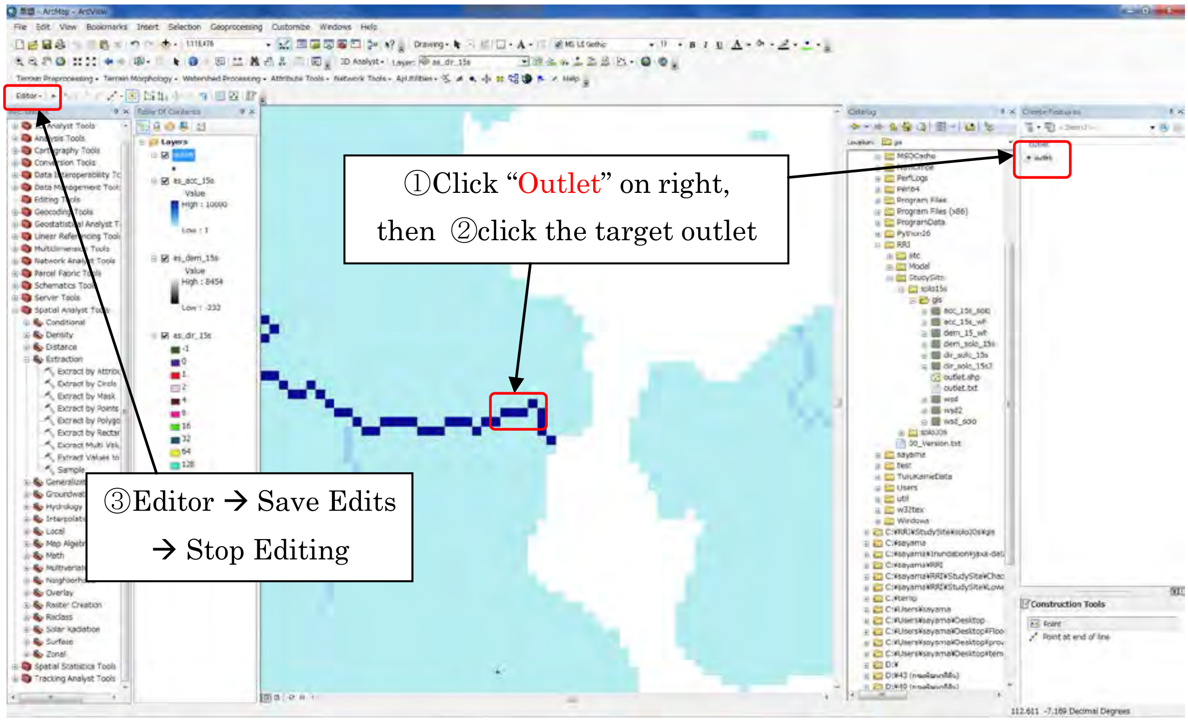
⑤ From the main menu [Customize] → [Toolbars] → [Editor]

On the Editor, choose [Start Editing], then Choose "Outlet" (the new Shapefile) to start editting.



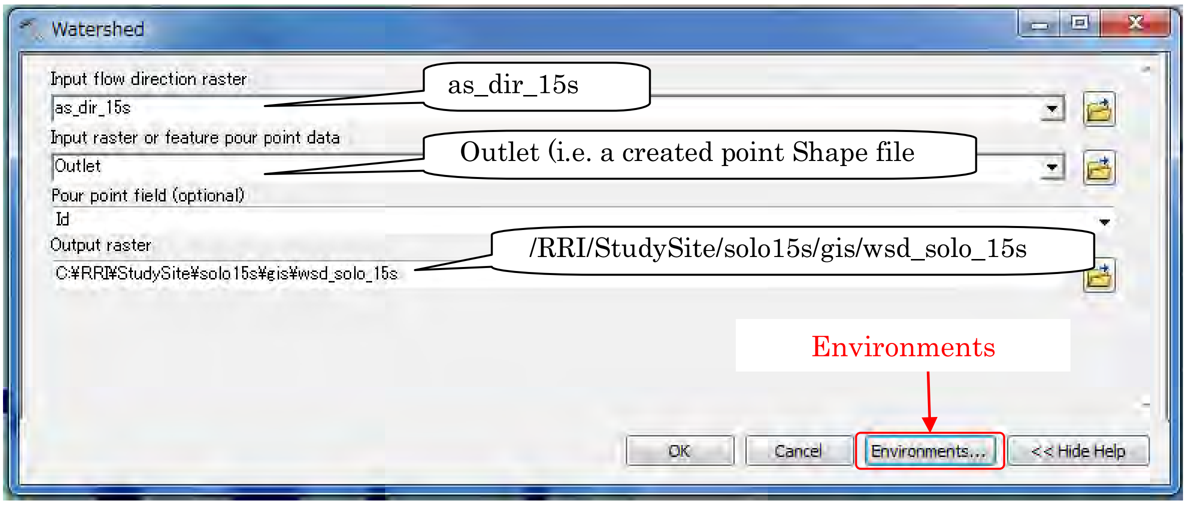
Clicking "Outlet", so that you can bring a point to indicate the target outlet.

After editting the outlet point, go to the editor menu to save and stop editing.

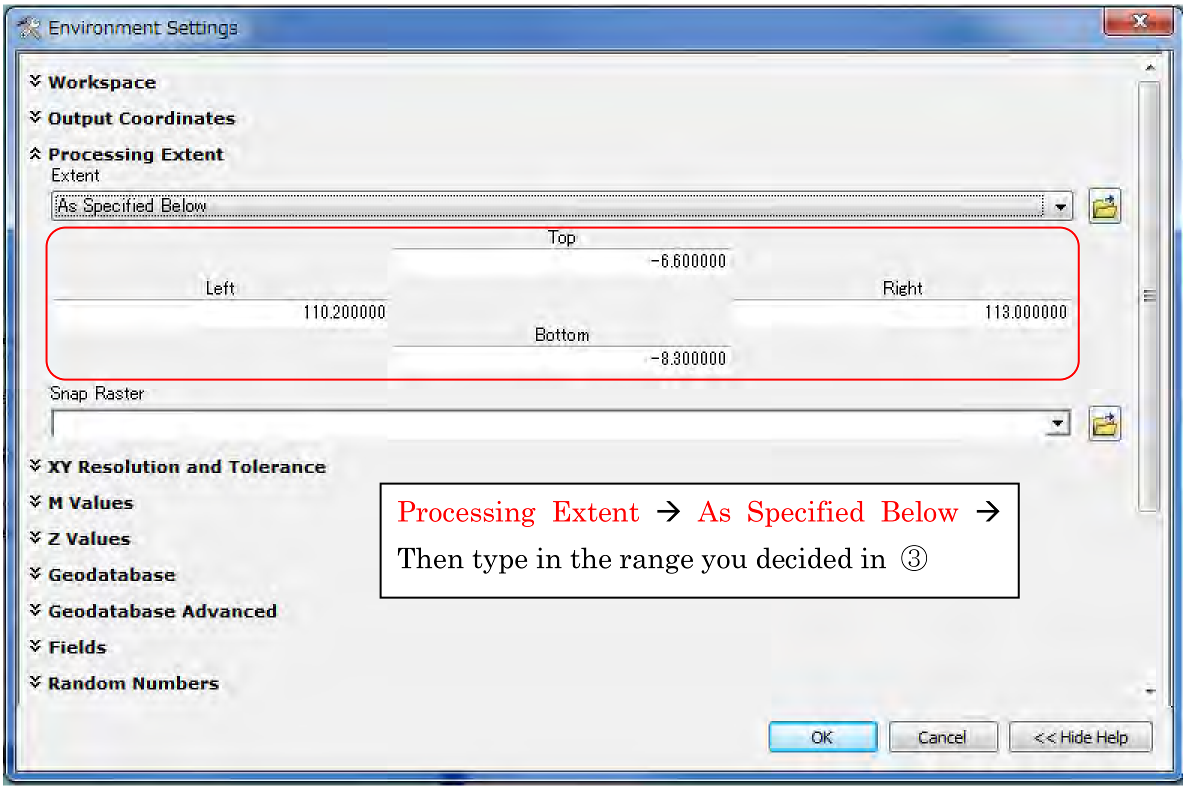


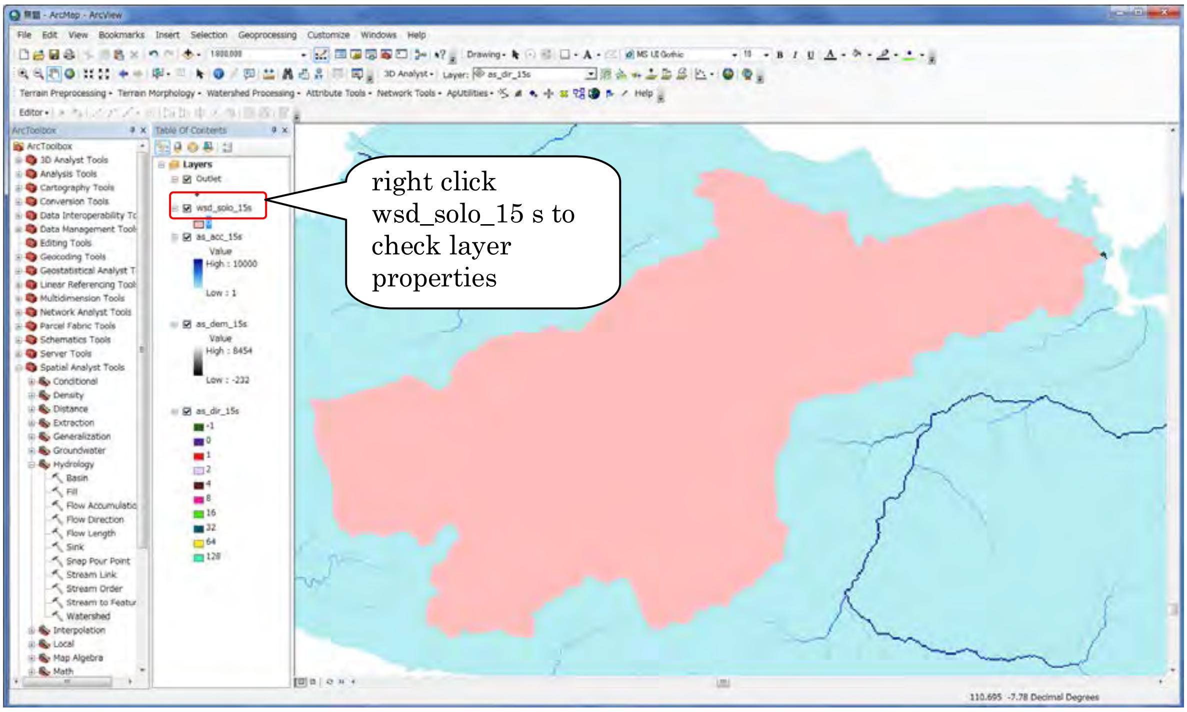
⑥ Using [ArcToolbox] → [Spatial Analyst Tools] → [Hydrology] → [Watershed], delineate a watershed with the defined outlet.

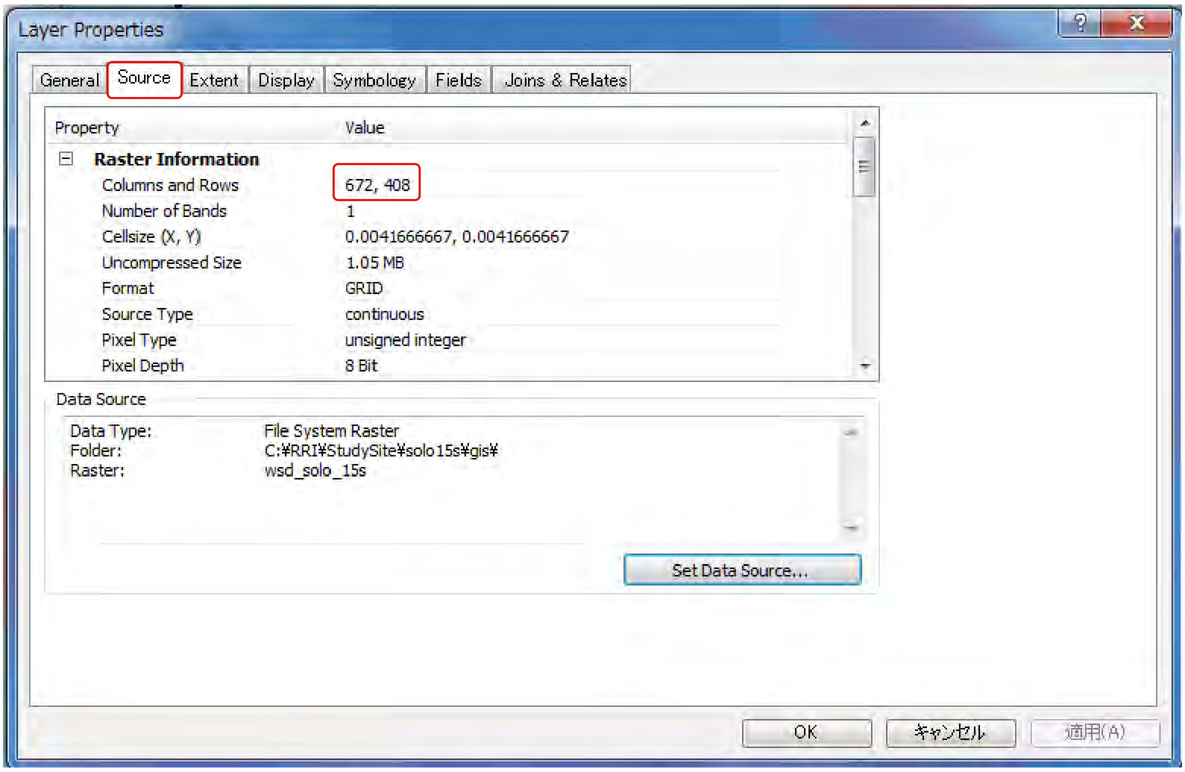
(IMPORTANT) To use [Spatial Analyst Tools] on ArcGIS, you must have the extension and activate it by choosing [Cusomize] → [Extentions] → add a check for [Spatial Analyst].



(IMPORTANT) Analysis range must be specified from the “environment” as below;

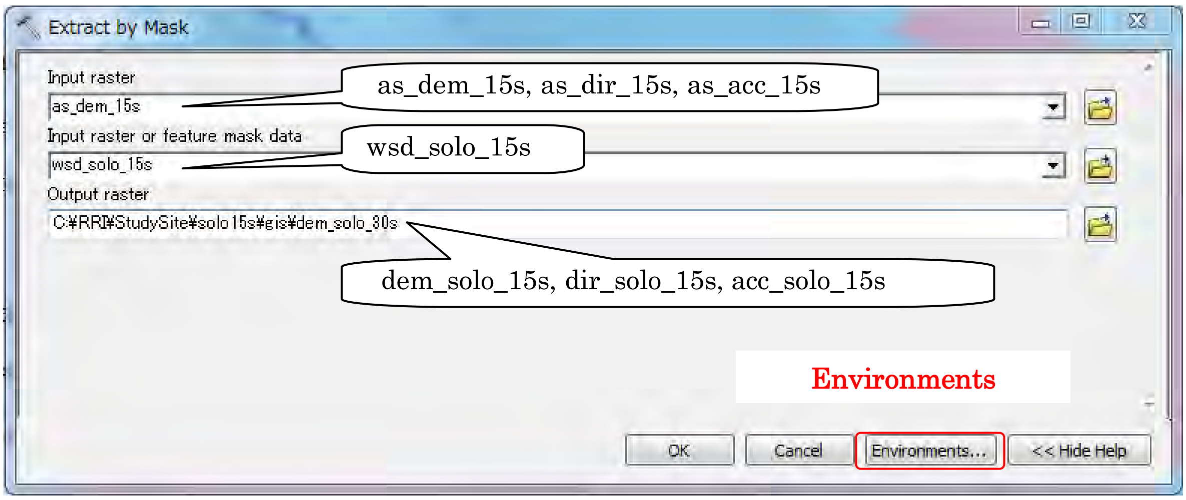

Environment Settings
Workspace
Output Coordinates
Processing Extent
Extent
As Specified Below
Top
-6.600000
Left
110.200000
Right
113.000000
Bottom
-8.300000
Snap Raster
XY Resolution and Tolerance
M Values
Z Values
Geodatabase
Geodatabase Advanced
Fields
Random Numbers
Processing Extent → As Specified Below →
Then type in the range you decided in ③
OK
Cancel
<< Hide Help


right click
wsd_solo_15 s to
check layer
properties

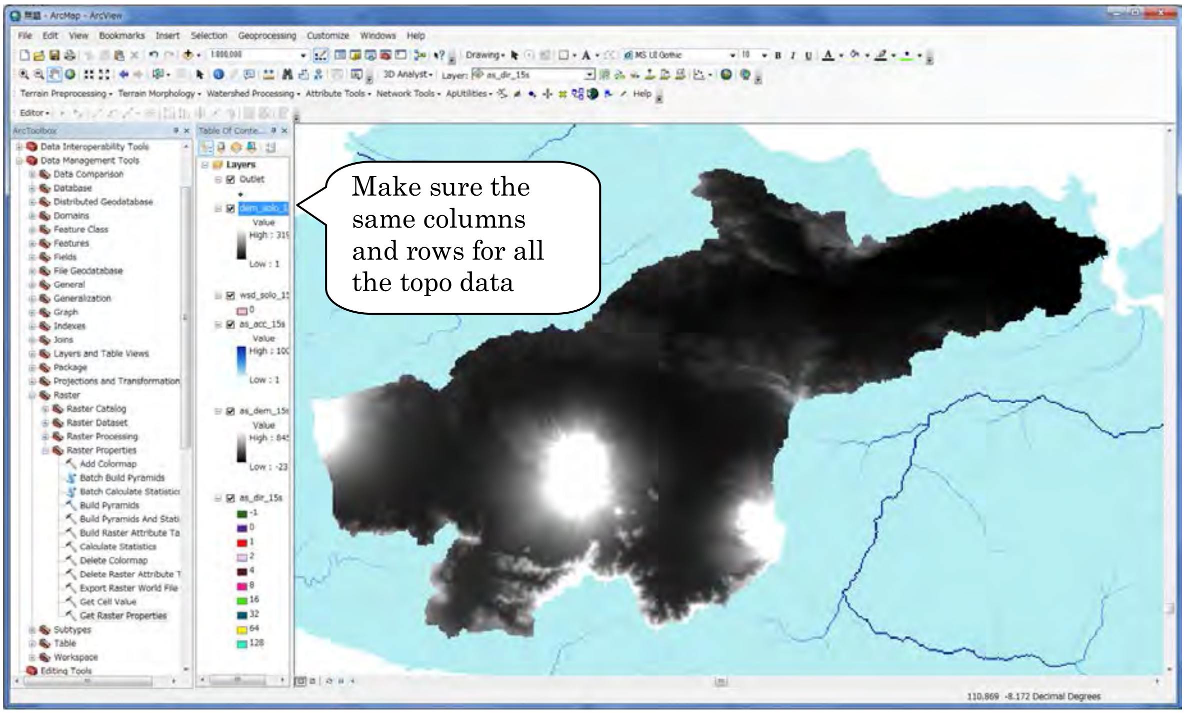


⑦ Right click the created watershed raster (e.g. wsd_solo_15s) and check layer properties. Under the "Source" tab, you can check "Columns and Rows". This will be the number of columns and rows for the topographic data used by RRI Model. If it exceeds more than 1000, using coarser resolution data is recommended to use.

⑧ Using [Spatial Analyst Tools] → [Extract] → [Extract by Mask], prepare dem (elevation), acc (flow accumulation) and dir (flow direction) masked by the delineated watershed.



(IMPORTANT) Analysis range must be specified from the "environment" the same as above.

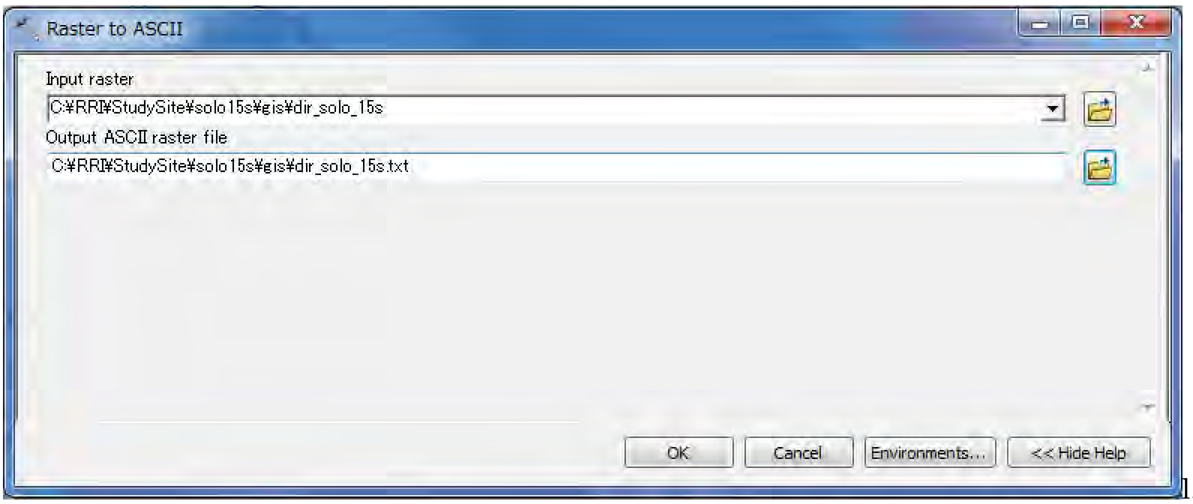


The above figure is the example of dem. The dir and acc must be also extracted in a same way.

3.3 Converting Raster Data to ASCII Data

To prepare input data files for RRI Model, convert all the processed data in ArcGIS Raster format to ASCII datasets.

Using [Conversion tool] → [Conversion from Raster] → [Raster to ASCII], perform conversion from raster to ASCII for all the three types of topography data.



The created ASCII data have the following format. Make sure once again all the three datasets have the same numbers in “ncols” and “nrows”.

```
ncols          673
nrows           409
xllcorner      110.2
yllcorner      -8.3
cellsize       0.004166666667
NODATA_value   -9999
 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

dir_solo_15s.txt

In the RRI model, the following three data must be prepared on the ASCII data format.

- DEM data (dem)
- Flow accumulation data (acc)
- Flow direction data (dir)

3.4 DEM Data Adjustment

There are some hollows in the original HydroSHEDS elevation data. Some of them represent actual topographic features, while some of them are caused due to the intrinsic characteristics of DEM. For example, deep and narrow valley, in which a river flows, may be blocked by surrounding topography because of the DEM resolution. In that case, the simulated water depths and river discharges with the original DEM are unrealistic.

Therefore, the following DEM adjustment is always recommended to avoid the unrealistic hollows in the original DEM. The provided program called demAdjust2 (/RRI/etc/demAdjust2) follows the flow direction of HydroSHEDS and remove all the negative slope along the flow direction by carving and lifting the original DEM.

The algorithm of demAdjust2 is as follows;

1. Based on the flow direction, demAdjust2 finds upstream cells (i.e. cells with no inflow).
2. Among the detected upstream cells, searching order is determined from the total length of the flow paths from each upstream cell to its most downstream cell.
3. Following the above decided order, demAdjust2 adjusts elevations based on the following procedures.

   1) The negative elevation is set to be zero.

   2) Lifting: If a single cell is extremely low (likely as a noise error) compared to its upstream and downstream cells, the cell's elevation will be replaced by the same elevation as the

upstream cell. The parameter "lift" is used as the threshold to detect sudden drop and its default value is set to be 500 m.

3) Carving: If the elevation suddenly increases along the flow direction, the cell's elevation will be replaced by the same elevation as the upstream cell. The parameter "carve" is used as the threshold to detect the sudden increase and its default value is 5 m.

4) Lifting and Carving: By searching from the most upstream, it finds a cell whose downstream elevation is higher than that cell (point L). By searching from point L toward downstream, it finds a cell whose downstream is lower than that cell (point H). The point L is lifted and point H is carved by the parameter "increment", whose default is 0.01 m.

The demAdjust2 program conducts each of the above procedure repeatedly for each flow path ways from all the detected upstream cells until all negative slopes are removed. Note that the above procedure does not change flow direction.

Run demAdjustment2 program in /RRI/etc/demAdjust2.

> The process is necessary even if a user would like to use original dem data. "demAdjust2" program modifies not only "dem" data but also flow direction data "dir". The modified "dir" (named as "adir") has flow direction equals to zero at outlet cells. This operation must be done and "adir" always must be used for RRI simulation. Also note that there is no correction for "acc", so use the original "acc" regardless the demAdjust2 procedure.

Read the adjusted dem and dir data to ArcGIS to visualize the data

Select [ArcToolBox] > [Conversion tool] > [Conversion from raster] > [ASCII→Raster].

"adem", "adir", "acc" are the three important topography data for the RRI simulation.

4. Preparing Input Rainfall Data

This section explains the method to prepare rainfall data for RRI Model. A user can prepare the data by any method as far as it follows a specified data format. Currently three program sets are prepared for processing:

1) gauged rainfall with Thiessen polygon interpolation (/etc/rainThiessen),

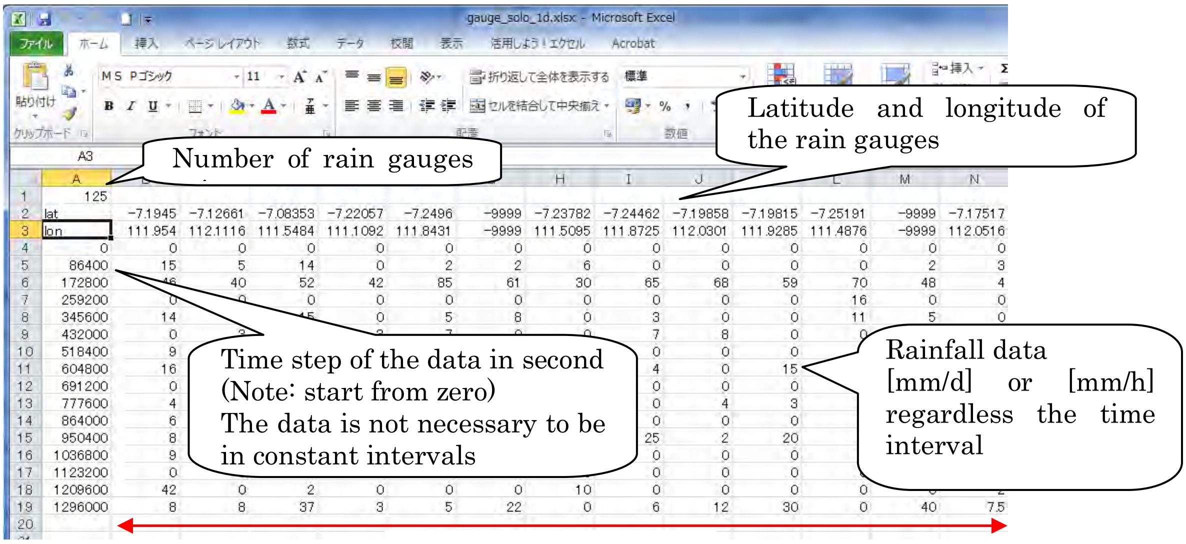
2) GSMaP satellite based rainfall (/etc/GSMaP) and

3) 3B42RT (/etc/3B42RT) satellite based rainfall.

4.1 Prepare Input Rainfall Data from Gauged Rainfall Records

To use ground gauged data for creating input rainfall for the RRI simulation, one can use /RRI/etc/rainThiessen/rainThiessen.f90 program.

① First, prepare rain gauge data in Excel (e.g. gauge_solo_1d.xlsx).



Set any negative value (e.g. -999) for missing data, not to be used for the interpolation.

② Select all cells having values, and copy and paste on a text editor. Then save it as txt file (e.g. gauge_solo_1d.txt)

③ Edit the input file "rainThiessen.txt" as follows.

```
./solo/gauge_solo_1d.txt
24
./solo/rain_solo_gauge_30s.dat
./solo/gauge_map_solo_30s.txt
ncols    336
nrows 204
xll 110.2
yll -8.3
cellsize 0.0083333333333333
```

1D rainfall data prepared above

Divide parameter
set 1 if the input rain data is in [mm/h],
set 24 if it is in [mm/d]

Output file names
L3 : output rainfall (i.e. input for RRI) [mm/h]
L4 : output map file (to check the spatial distribution of rain gauges)

Coordinate specifications of the output rainfall file. One can copy and paste the header of a topographic file (i.e. dem).

However any coordinates values and cellsize can be specified as far as the same coordinate is set in “RRI_Input.txt” and the range covers an entire domain. See the detail in Section 8.2.

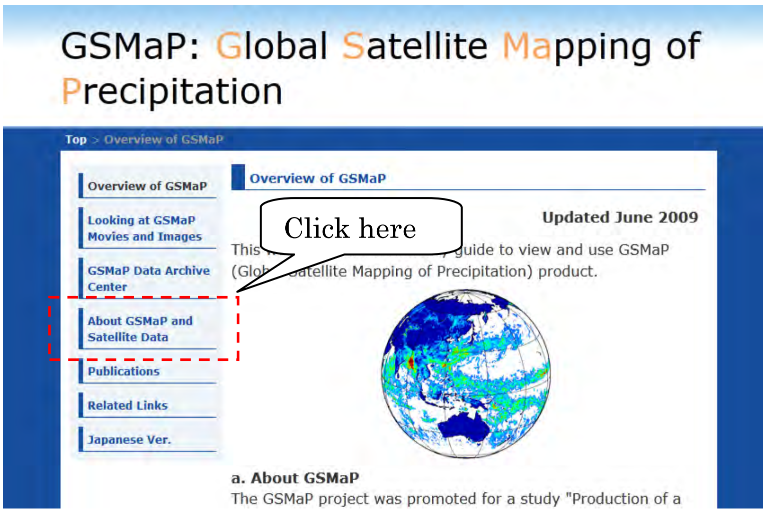
④ Run rainThiessen program.

⑤ The created output file (e.g. “rain_solo_30s_gauge.dat”) can be copied to /RRI/Model/input/ and used as the input rainfall.

4.2 Prepare Input Rainfall Data from GSMaP

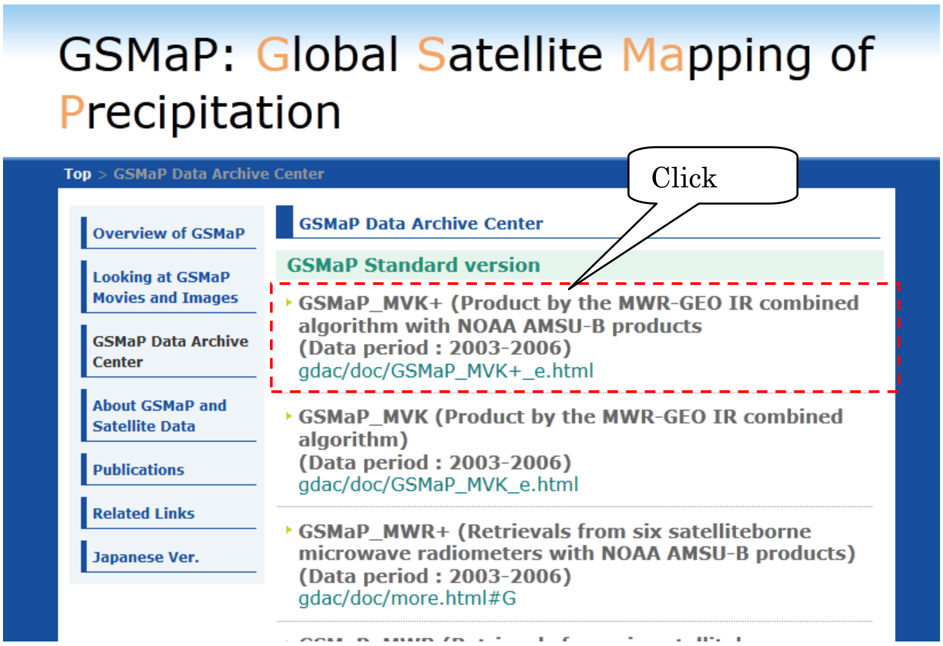
4.2.1 Download GSMaP Data

① Open the following GSMaP web site with a web browser, and click on the link to the GSMaP Data Archive Center.



(http://sharaku.eorc.jaxa.jp/GSMaP_crest/index.html)

② Click on “GSMaP_MVK+” as the data to be downloaded.



Then choose hourly or daily rainfall data to download. Note that this link allows you to download the data only between 2003 and 2006. For the data after 2006, you must register through the same website to obtain the password and download GSMaP NRT product.

4.2.2 Calculate Rainfall Data Range for a Target Catchment

To calculate the suitable range for the delineation, /etc/GSMaP/calc_area.f90 program can be used. Before using /etc/GSMaP/calc_area.f90 program, the following "ncols" to "cellsize" must be replaced for your target catchment. These parameters can be found from the headers of topographic files of "dem", "acc" or"dir" prepared for the target catchment.
Do not forget to compile the Fortran program before the execution.

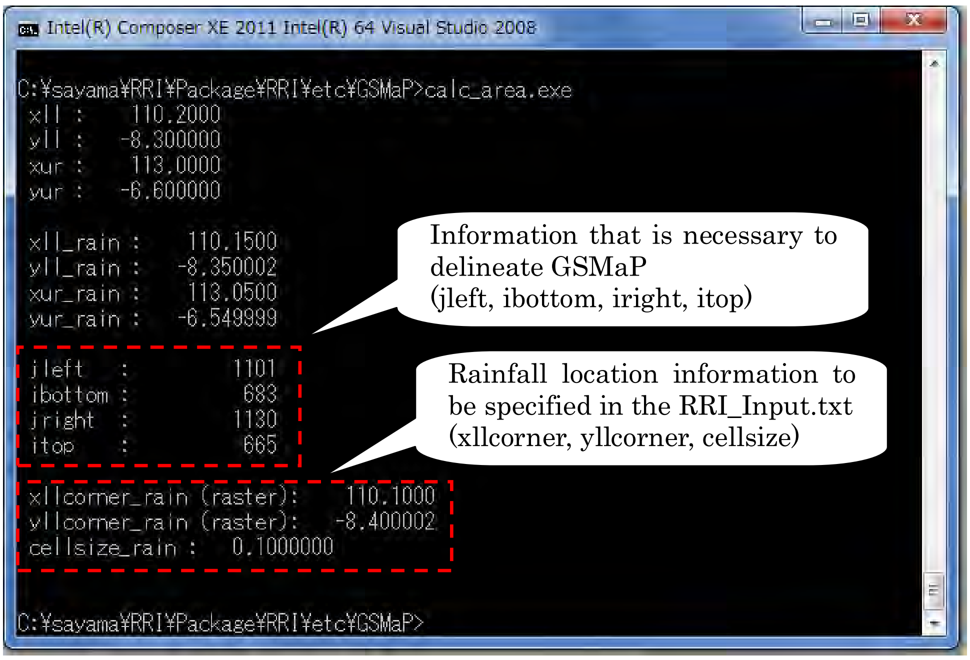
calc_area.f90

```
! Compute suitable range of GSMaP data for a target catchment

! INPUT : Replace the following values from DEM, DIR, ACC file
integer ncols, nrows
real xllcorner, yllcorner, cellsize

! Solo (30 sec)
parameter( ncols = 336 )
parameter( nrows = 204 )
parameter( xll = 110.2 )
parameter( yll = -8.3 )
parameter( cellsize = 0.008333333333 )

! IMPORTANT: Spatial Resolution of Rainfall Data
real cellsize_rain
parameter( cellsize_rain = 0.1 ) ! Hourly
!parameter( cellsize_rain = 0.25 ) ! Daily

integer itop, ibottom, jleft, jright

real xul_data, yul_data ! Origin of the Data
parameter( xul_data = 0.05 )
parameter( yul_data = 59.95 )
```

Must be the same as the headers of topographic data ncols, nrows, xll, yll, cellsize

Check resolution of rainfall data 0.1 : hourly 0.25 : daily for GSMaP

The following information can be obtained by running “calc_area.exe”.



4.2.3 Delineating GSMaP Data for Target Area

① First, save GSMaP rainfall data in a folder (e.g. infile).

② Execute the bat file "/etc/GSMaP/makeList.bat" to prepare a file list named as "list.txt"

```
dir /b infile > list.bat
```

Revise the pass, then save and execute.

When executed, [list.txt] is created

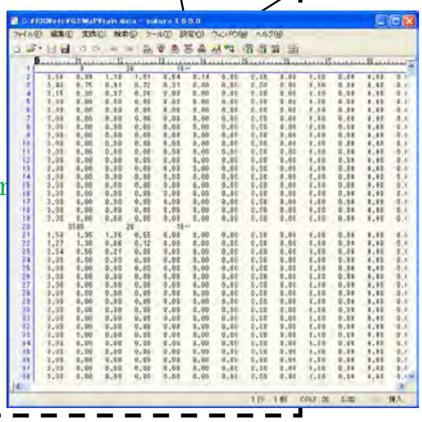
③After revising the following, compile and execute [read_GSMaP_0.1deg.f90.]

read_GSMaP_0.1deg.f90

```
! Read GSMaP binary data and convert it to ASCII format,
! which can be read by RRI Model
!
! list.txt file must be prepared in advance by using make.bat
!
character*256 listfile
parameter( listfile = "list.txt" )

! input folder
character*256 infile1, infile
parameter( infile1 = "./infile/" )
character*256 cutfile1, cutfile
parameter( cutfile1 = "./cutfile/" )
character*256 rainfile
parameter( rainfile = "rain.data" )
character*256 sumfile
parameter( sumfile = "sumRain.data" )

! Target Area
integer jleft, ibottom, jright, itop

! The range to delineate
! The values can be calculated by calc_area.f90 program
! for a target catchment
parameter( jleft     = 1101 )
parameter( ibottom = 683 )
parameter( jright    = 1130 )
parameter( itop      = 665 )
```

Designate the path of the rainfall data folder

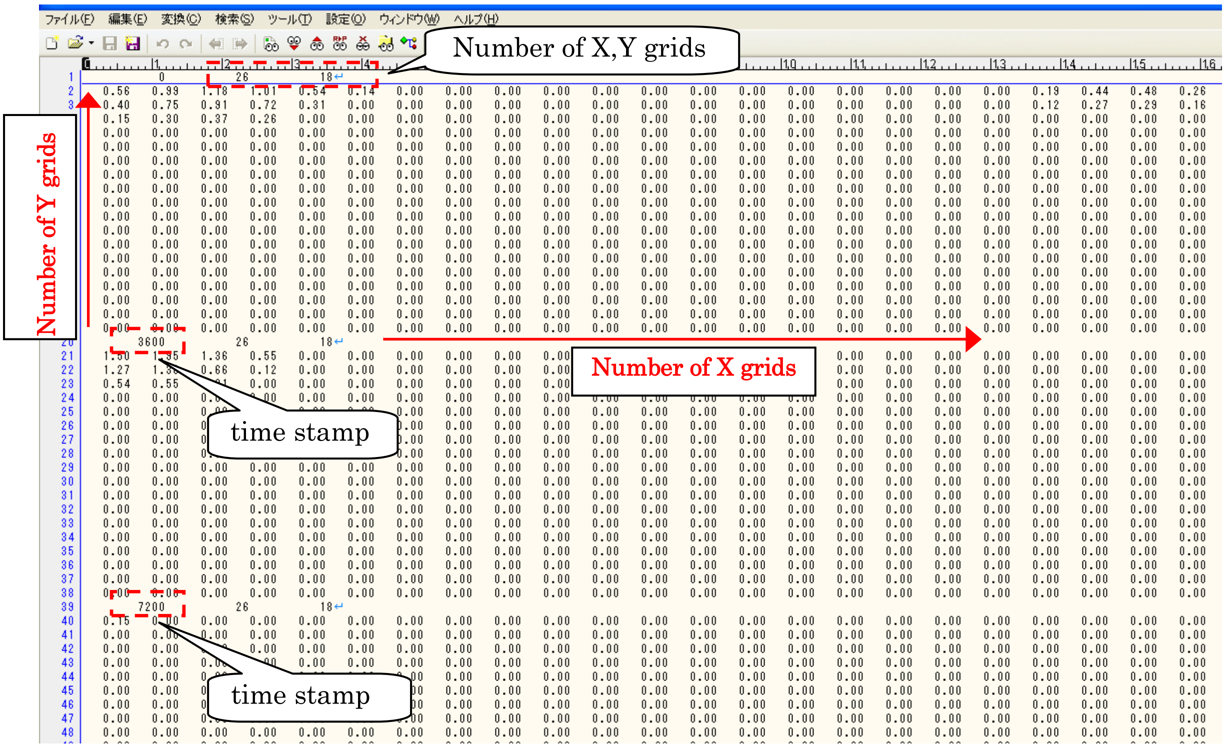
Running the program creates "rain.data", which is rainfall input file for RRI simulation



Designate the delineation range

4.3 Format of Input Rainfall Data for RRI Model

Here is the format of the input rainfall data used for RRI Model. By specifying the cell size, xll_corner and yll_corner of the rainfall data into a control file of RRI model (i.e. "RRI_Input.txt"), the model can overlay the rainfall distribution even if the ranges and the resolutions are different from topographic data as far as the rainfall data covers all the simulation extent.



※ The input unit of rainfall must be always **mm/hr**.

※ The time interval is not necessary to be constant.

※ Rainfall between 3600 and 7200 is written under the time stamp of 7200 (just like rain gauge data).

【RRI_Input.txt】・・・Control file of the RRI Model

```
RRI_Input_Format_Ver1_3

./infile/solo30s/rain_solo_30s_gauge.dat
./infile/solo30s/adem2_30s_solo.txt
./infile/solo30s/acc_30s_solo.txt
./infile/solo30s/adir_30s_solo.txt

0                    # utm(1) or latlon(0)
1                    # 4-direction (0), 8-direction(1)
360                  # lasth
600                  # dt
60                   # dt_riv
96                   # outnum
110.2d0              # xllcorner_rain
-8.3d0               # yllcorner_rain
0.00833333d0 0.00833333d0    # cellsize_rain

1                    # num_of_landuse
1                    # diffusion(1) or kinematic(0)
0.0d0                # dm
0.0d0                # da
```

RRI_Input.txt

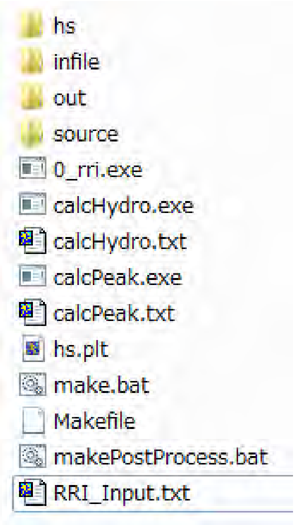
Coordinates and grid size of the south-west end of the rainfall data range

5. Conditions Setting for RRI Simulation

5.1 Folder Configuration

The following shows the folder configuration and roles of each folder in /RRI/Model

[/RRI/Model]



-Folders-

infile : Stores following sets of input data for each project

- Adjusted topography data (adem)
- Flow accumulation data (acc)
- Adjusted flow direction data (adir)
- Rainfall data

(optional)

- Land use data
- Initial and boundary conditions

out : Stores simulation results for each output time step

- hr_ : River water depth [m]
- hs_ : Slope water depth [m]
- qr_ : River discharge [m^3/s]
- qu_ : Slope discharge for x direction [m^3/s]
- qv_ : Slope discharge for y direction [m^3/s]
- gampt_ff : Green-Ampt cumulative water depth [m]
- storage.dat : water balance checking file

source : Fortran source programs of RRI Model

hs : Stores figures of inundation depths (hs) by gnuplot

【Important Files】

- make.bat : Compiling RRI model source code (use Makefile for UNIX/LINUX)
- 0_rri.exe: RRI model execution file
- RRI_Input.txt : RRI model control file

【Other Programs and Files】

- makePostProcess.bat : Compiling calcHydro.exe and calcPeak.exe
- calcHydro.exe : hydrograph calculation program (post processing)
- calcPeak.exe : peak inundation depth calculation program (post processing)
- hs.plt : gnuplot script to create inundation depths figures (prepared by /etc/prepHsPlt)

5.2 RRI Model Control File (RRI_Input.txt)

RRI_Input.txt

```
L1   RRI_Input_Format_Ver1_3
L2
L3   ./infile/solo30s/rain_solo_30s_gauge.dat
L4   ./infile/solo30s/adem2_30s_solo.txt
L5   ./infile/solo30s/acc_30s_solo.txt
L6   ./infile/solo30s/adir_30s_solo.txt
L7
L8   0                        # utm(1) or latlon(0)
L9   1                        # 4-direction (0), 8-direction(1)
L10  360                      # lasth [hour]
L11  600                      # dt [sec]
L12  60                       # dt_riv [sec]
L13  96                       # outnum [-]
L14  110.2d0                  # xllcorner_rain
L15  -8.3d0                   # yllcorner_rain
L16  0.00833333d0 0.00833333d0      # cellsize_rain
L17
```

Note that #comment is allowed only for lines with numbers like L8 to L16, but it is not allowed for lines with characters like L3 to L6.

L1 : Version of the control file format.

This version has to be compatible with the RRI program version. When RRI Model version is updated, user may be requested to modify this control file to be suitable for the updated version.

L3 – L6 : Paths of the input files (rainfall, dem, acc, dir)

Note that adjusted direction file having zero at the outlet must be read in the flow direction column. This adjustment (for dem and dir) can be implemented through the process of demAdjust2.

L8 : Topographic and rainfall data coordinate system (UTM (1) or Lat Lon(0))

L9 : Simulating with 4- (0) or 8-direction (1) by the two dimensional model [default : 1]

L10 : Simulation period [hour]

L11 : Simulation time step [sec], [default : 600 sec]

L12 : Simulation time step for river [sec], [default : 60 sec]

The above time steps are just initial setting. The adaptive Runge-Kutta algorithm used for RRI simulation may shorten the time steps if necessary.

L13 : Number of output files

Simulation period specified above is equally divided for simulation output.

L14 – L16 : South west coordinate and resolution of rainfall data

Number of col and row are written in the rainfall data.

RRI_Input.txt

```
L18  1             # num_of_landuse
L19  1             # diffusion(1) or kinematic(0)
L20  0.0d0         # dm
L21  0.0d0         # da
L22  0.0d0         # ka
L23  0.0d0         # beta
L24  0.0d0         # soildepth
L25  0.4d0         # ns_slope
L26  0.03d0        # ns_river
L27
L28  0.d0            # ksv
L29  0.275d0         # delta
L30  0.3163d0        # faif
L31  -1.d0           # infilt_limit (-1.d0 -> no limit)
L32
```

L18 : Number of landuse

Parameter sets specified below should correspond to the number of landuse specified here. For example, if there are three landuse types in a catchment, write three different parameter sets. Prepare also the landuse map which has numbers from one to three, so that the parameter sets described below will be assigned to each landuse grid cell. First column parameters are assigned to landuse type "1" in the landuse map.

L19 : diffusion (1) or kinematic (0) [default : 1]

The default mode of RRI model uses diffusion wave equations. However, by setting zero here, RRI model can use kinematic wave approximation.

L20 – L25 : saturated subsurface and surface model parameters

L20 and L23 are options to consider unsaturated subsurface flow in lateral direction. To begin with, set zero for "dm" to inactivate this option.

"da" defines maximum water depth in saturated subsurface flow. Setting zero makes no saturated subsurface flow consideration. See 8.7 for the details of the parameter settings.

L26 : Manning's roughness in river channel

L28 – L31 : Green-Ampt infiltration model parameters

Set ksv = 0 for inactivating Green-Ampt infiltration model.

"ksv" : vertical saturated hydraulic conductivity [m/s]. "delta" is soil porosity minus initial water volume content $(\phi - \theta_i)$. "faif" is the suction at the wetting front defined by S_f.

L31 sets the maximum cumulative infiltration depths in meter. Once the cumulative infiltration depths reaches to this maximum depths, no more infiltration happens at the grid-cells. (If infilt_limit [m] is zero, no infiltration, if infilt_limit is -1.0, no limitation.)

RRI_Input.txt

```
L33  20                    # riv_thresh
L34  5.0d0                 # width_param_c
L35  0.35d0                # width_param_s
L36  0.95d0                # depth_param_c
L37  0.20d0                # depth_param_s
L38  0.d0                  # height_param
L39  20                    # height_limit_param
L40
L41  0
L42  ./infile/solo/width_solo.txt
L43  ./infile/solo/depth_solo.txt
L44  ./infile/solo/height_solo.txt
L45
```

L33 – L39 : River channel geometry setting by equations

$$width = c_w A^{s_w}$$

$$depth = c_d A^{s_d}$$

The above equations are used as default settings for river channel widths and depths.

Note that A in the equations is the upstream catchment area [km^2] for each river grid-cell.

L41 – L44 : River channel geometry setting by files (optional)

If one would like to set width, depth and embankment height from files instead of the above equations, set 1 in L41 and prepare the files in ESRI/ASCII format.

RRI_Input.txt

```
L46  0.d0                 # init_cond_slo
L47  0.d0                 # init_cond_riv
L48
L49  0 0 0
L50  ./infile/hs_init_dummy.out
L51  ./infile/hr_init_dummy.out
L52  ./infile/gamptff_init_dummy.out
L53
L54  0 0
L55  ./infile/hs_wlev_bound_dummy.txt
L56  ./infile/hr_wlev_bound_dummy.txt
L57
L58  0 0
L59  ./infile/hs_disc_bound_dummy.txt
L60  ./infile/hr_disc_bound_dummy.txt
L61
```

L46 – L47 : Initial water depths on slope and river (optional) [Default : 0.d0]

L49 – L52 : Initial water depth on slope, river and GA Model cumulative by files (optional)
If one would like to set initial water depths on slope and river for each grid cell, set 1 in L49 and prepare the initial condition distribution files specified in L50, L51 and L52. Note that the format of the files is the same as RRI model output.

L54 – L56 : Water depths boundary conditions (optional)
L55 : Slope water depths boundary conditions, L56 : River water depths boundary conditions
Format of the boundary condition files is the same as rainfall data format, but the number of grid-cells must be the same as the topographic data including dem, dir, and acc. Time stamps in the boundary condition can vary within the file.

From ver 1.3.2 of RRI Model, boundary condition files can be also prepared in one dimensional way (i.e. time series data for specific points), instead of the time series of the two dimensional data, to reduce the size of boundary condition files. To use the second option, **use flag "2" in L54**, instead of "1" in L54. (See details Section 8 for the details of boundary condition settings.

L58 – L60 : Water discharge boundary conditions (optional)
(Same as L54 – L56)
(Use the flag "2" if the discharge boundary condition files are prepared in 1D format)

RRI_Input.txt

```
L62  0
L63  ./infile/solo/landuse_solo.txt
L64
L65  0
L66  ./infile/damcnt_ALL.txt
L67
L68  0
L69  ./infile/div_dummy.txt
L70
L71  0
L72  ./infile/potentialET.txt
L73  110.2d0                  # xllcorner_evp
L74  -8.3d0                   # yllcorner_evp
L75  0.00833333d0 0.00833333d0      # cellsize_rain
L76
```

L62 – L63 : Landuse setting (optional)

If one would like to use multiple parameter sets for different grid-cells, set 1 in L62 and read landuse file specified in L63.

L65 – L66 : Dam condition setting (optional)

RRI model simulates the effect of dam reservoir operations based on simple rule. Refer to the source code "RRI_Dam.f90" for details. (See also 8.11)

L70 – L71 : River diversion setting (optional)

River channel diversion setting (See also 8.10)

L71 – L75 : Evapotranspiration setting (optional)

Prepare ET file and specify the path on L72. The format of ET file is the same as rainfall. The resolution and xll and yll corners can be different from the rainfall file as far as it covers all the simulation domain.

RRI_Input.txt

```
L77  1 1 1 0 0 0 0
L78  ./out/hs_
L79  ./out/hr_
L80  ./out/qr_
L81  ./out/qu_
L82  ./out/qv_
L83  ./out/gampt_ff_
L84  ./out/storage.dat
L85
L86  0
L87  ./tecout.dat
```

L77 – L84 : Output file settings

Change the settings of L77 to "1" to output different sets of simulation results listed in the same order between L78 and L84

L86 – L87 : Output simulation results in Tecplot format (Optional)

Set 1 in L86 if one wants to get the input input file for Tecplot to visualize simulation results.

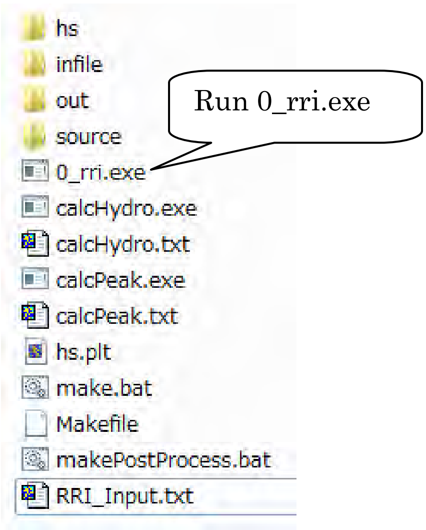
6. Running RRI Model

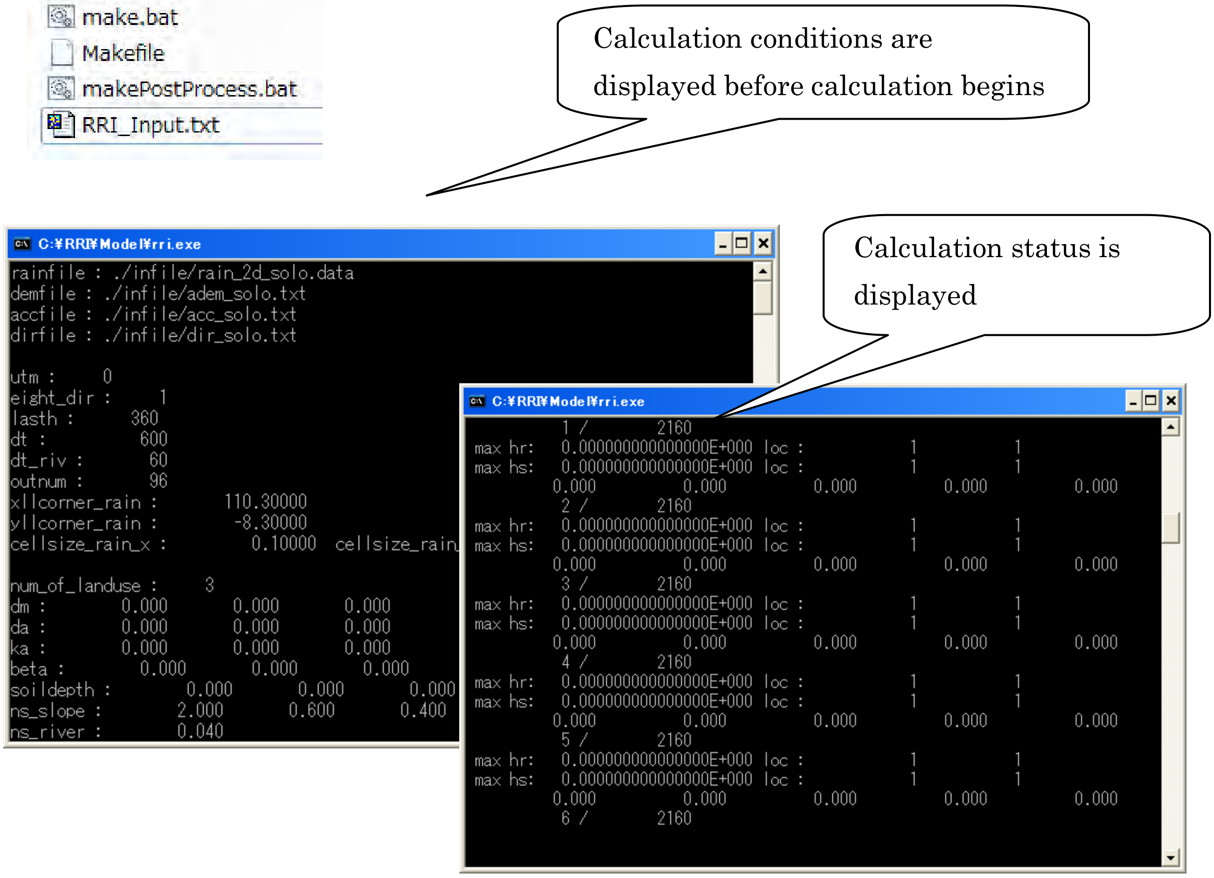
① Compiling RRI Model using make.bat

② Prepare "RRI_Input.txt" in "/RRI/Model/" folder (One can copy the sample of input file from /RRI/Model/infile/).

③ Execute "0_rri.exe", which reads the RRI_Input.txt stored in the same folder.

※For the folder configuration and roles of each folder of the RRI model, see Section 5



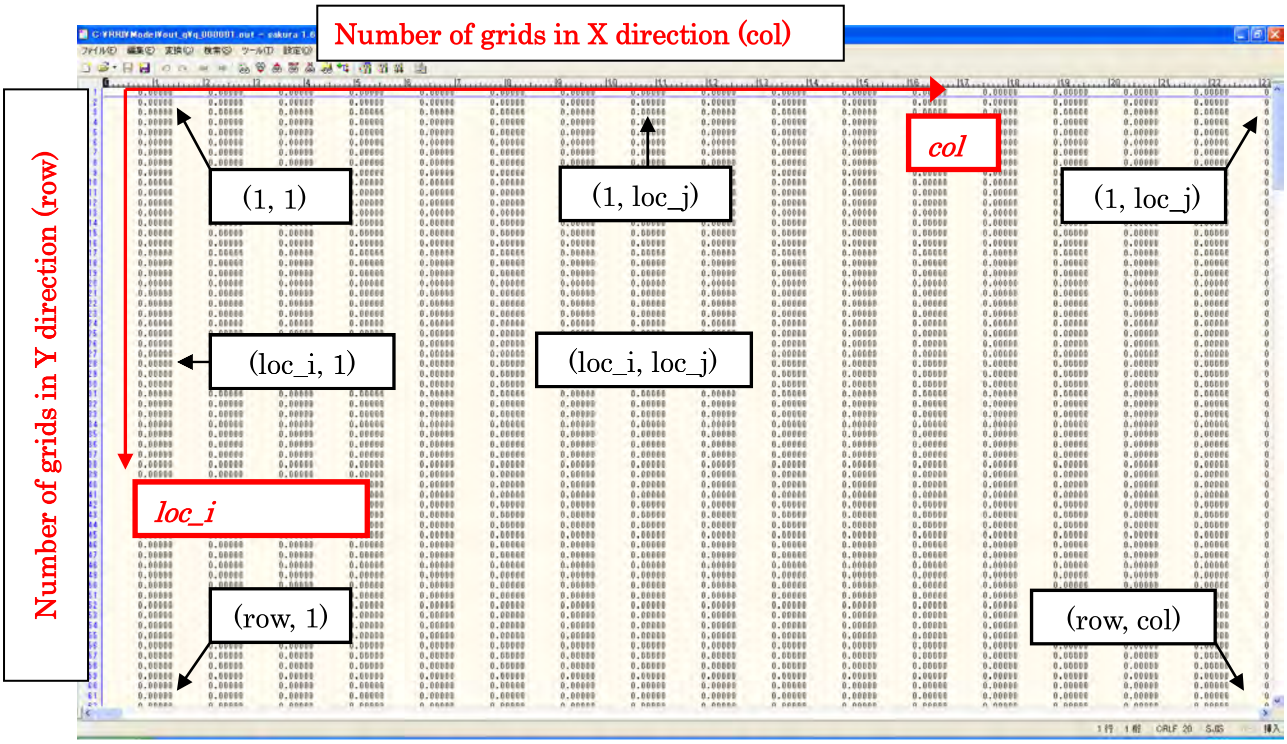


7. Plotting Output Data

This section explains how to plot RRI Model output.

7.1 Format of the Output Files

Each output file contains water depths on slope (hs_) and on river (hr_) and river discharges (qr_) on river at a particular time step. The units of the output are [m] for water depths and [m^3/s] for discharge.



※The numbers of rows and columns are the same as those of the topographic data.

Note that for each type of model output, the number of the files is defined in RRI_Input.txt (L13 : outnum). The simulation period is equally divided by "outnum" and the number assigned to each output file represents the output time stamp.

7.2 Visualize Inundation Depth with GNUPLOT

GNUPLOT can be used to illustrate flood inundation depth distributions. In RRI/Model, the GNUPLOT script named "hs.plt" is included. To change the settings, one can edit "hs.plt" directly or create another "hs.plt" by using a Fortran program named "prepHsPlt.f90" saved in "RRI/etc/prepHsPlt".

① Edit “hs.plt” file to change the configurations.

hs_plt.txt

```
reset

set terminal gif medium size 672, 408 crop

set pm3d map
set palette defined (0.0 "gray", 1.5 "blue", 3 "green")

set xrange [0:]
set yrange [:] reverse
set zrange [0:] reverse

#set xrange [180:200]
#set yrange [435:455] reverse

set cbrange[0.:3]
set zrange[0.0:]

set output "./hs/hs_000001.gif"
splot "./out/hs_000001.out" matrix t "000001 / 000096"

set output "./hs/hs_000002.gif"
splot "./out/hs_000002.out" matrix t "000002 / 000096"

set output "./hs/hs_000003.gif"
splot "./out/hs_000003.out" matrix t "000003 / 000096"
```

The size of output GIF file, X and Y direction. Use the same X and Y ratio as DEM’s col and row.

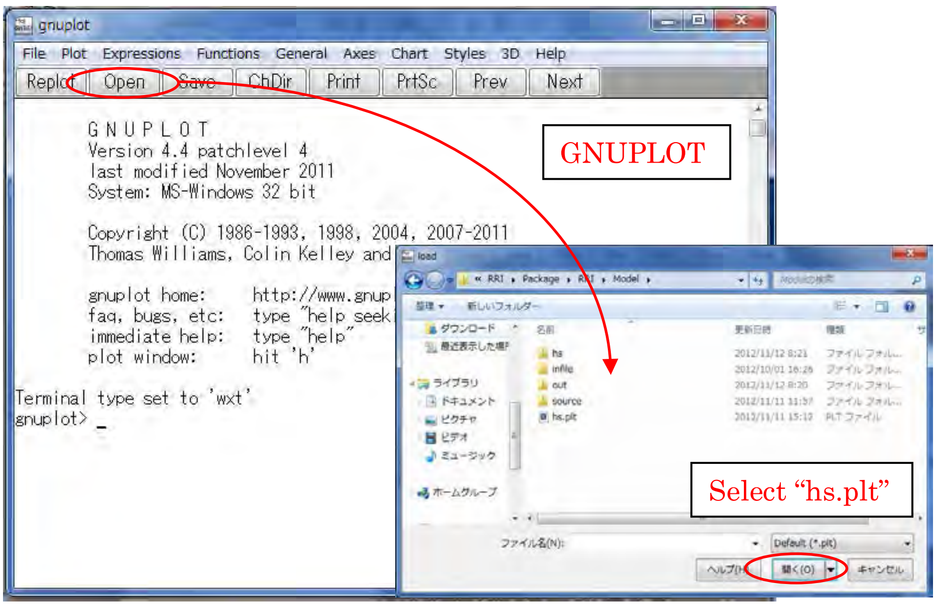
Color pattern settings

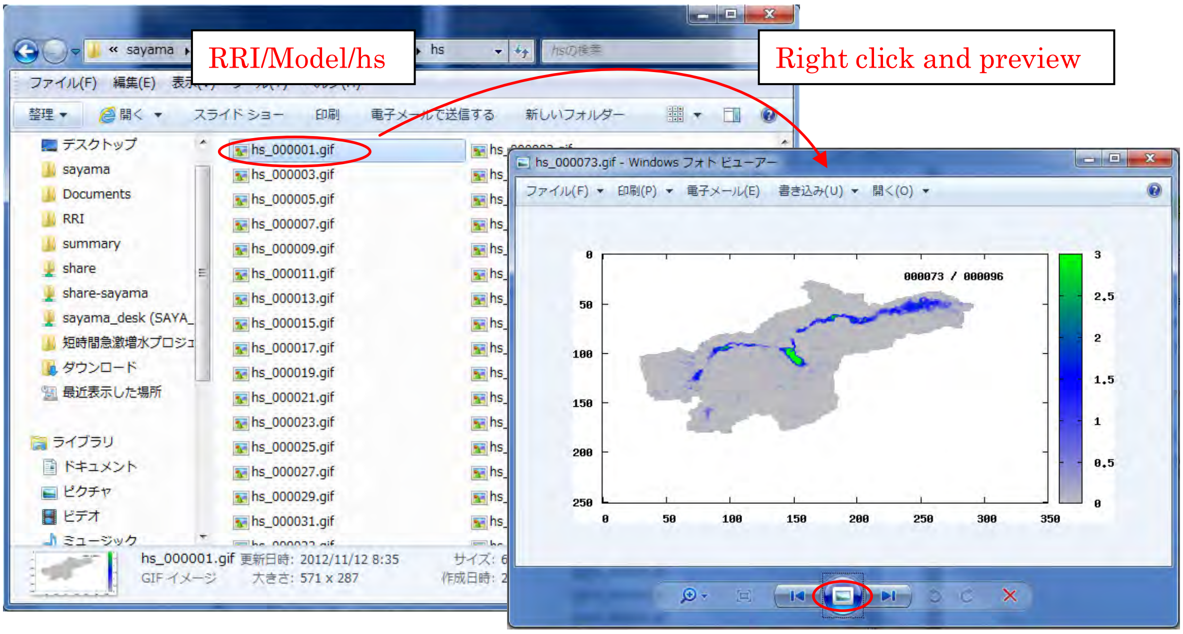
Color range

From RRI output (hs_***.out) to gif

② Start GNUPLOT program by clicking “/RRI/etc/gnuplot/binary/wgnuplot.exe”

Then open and select “hs.plt” script file.





7.3 Hydrographs at Specific Locations

A Fortran program named “calcHydro.exe” can be used to generate hydrographs by picking up values from “out/qr_***.txt” at specified locations.

① Edit “RRI/Model/calcHydro.txt” (see more details “RRI/etc/calcHydro/00_readme.txt”)

L1 : [In] location file (e.g. ./infile/solo30s/location_30s_solo.txt)

L2 : [In] RRI output file (e.g. ./out/qr_)

L3 : [Out] hydrograph file (e.g. ./infile/solo30s/disc_)

calcHydro.txt

```
./infile/solo30s/location_30s_solo.txt
out/qr_
./infile/solo30s/disc_
```

location_30s_solo.txt

```
Cepu 68 167
(list all target locations)
```

② Run “calcHydro.exe”. (Execute “makePostProcess.bat” in advance to compile.)

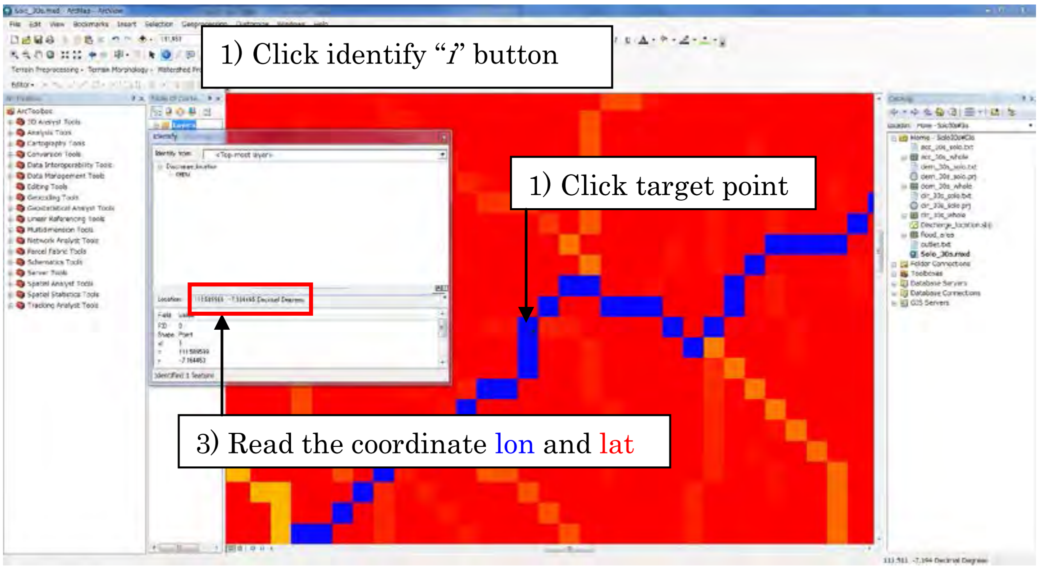
③ Check the created files specified in L3 of “calcHydro.txt”. (e.g. ./infile/solo30s/disc_)

④ From GNUPLOT screen, open and select “hydrograph.plt”, which is a GNUPLOT script file to plot hydrographs. Any other plotting software, such as Excel, can be also used to draw hydrographs from created files (e.g. ./infile/solo30s/disc_Cepu.txt).

In the location file (e.g. ./infile/solo30s/location_30s_solo.txt), one can list all target points, which you want to calculate hydrographs. Write the "*name of location*" and "loc_i" (y-direction) and "loc_j" (x-direction)
Note that "loc_i" is the row (y-direction from top) and "loc_j" is the col (x-direction from left).

To identify the observation points in mesh coordinate (loc_i, loc_j), one can use "/RRI/etc/coordinate.xlsx" to calculate based on the coordinate in latitude(y) and longitude(x).

① Find the latitude (y) and longitude (x) of the observation point using ArcGIS.



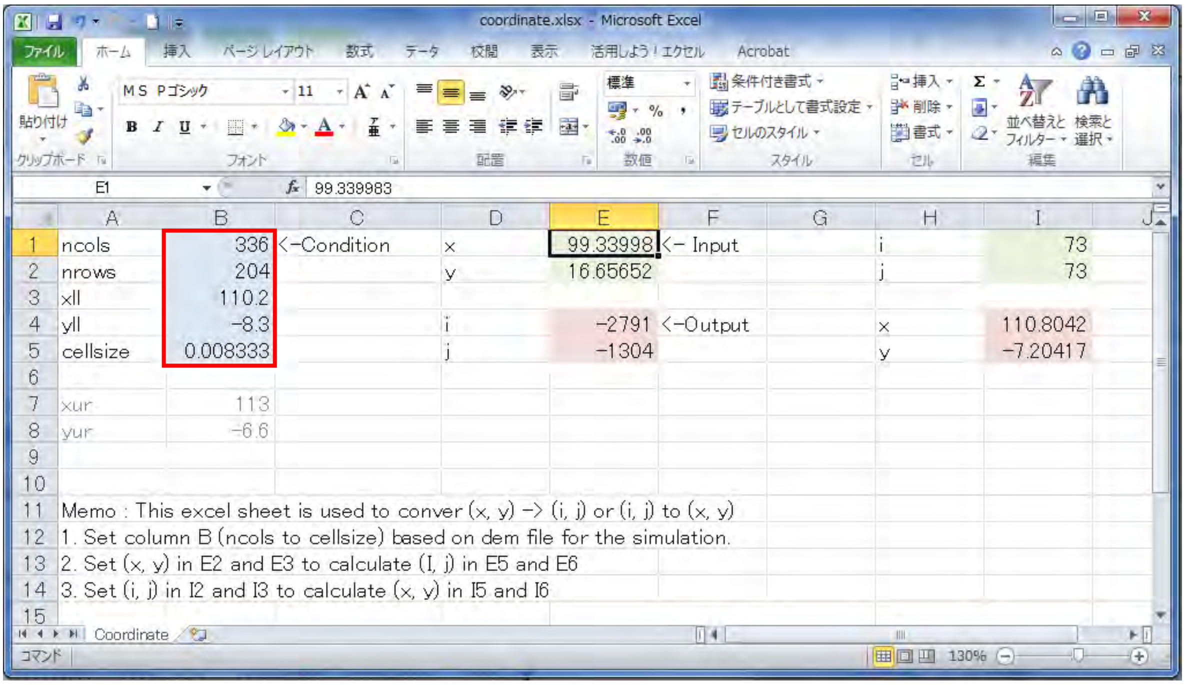
(Displaying "acc" on top to make sure the selected point is on a river grid cell.)

② Open one of the topographic data (i.e. dem, dir, or acc)

acc_solo_30s.txt

```
ncols          336
nrows           204
xllcorner      110.2
yllcorner      -8.3
cellsize       0.00833333333333
NODATA_value   -9999
 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
```

③ Read the header part (red box in the above figure) of the topographic data and copy the same information in the excel file (i.e. /RRI/etc/coordinate.xlsx).



④ Type x and y (or lon and lat) coordinate of the target point, then the calculated mesh coordinate (loc_i, loc_j) appears in (E4, E5).

(“coordinate.xlsx” can be used also to convert from (loc_i, loc_j) to (lon, lat).

7.4 Visualize Peak Inundation Depths

Fortran program named “calcPeak.exe” can be used to compute the maximum flood depths based on RRI Model output (“out/hs_*.out”). See 2.2.3 the procedure more in detail.

① Edit “RRI/Model/calcPeak.txt” file after RRI model execution.
In “calcPeak.txt”, L1 sets the path of dem file, L2 sets the RRI model output file to calculate the peak, and L3 sets the number of output files. L4 defines the output file of calcPeak program. See details the readme file of “/etc/calcPeak”.

② Execute “calcPeak.exe”. (Execute “makePostProcess.bat” if the executable file does not exist.)

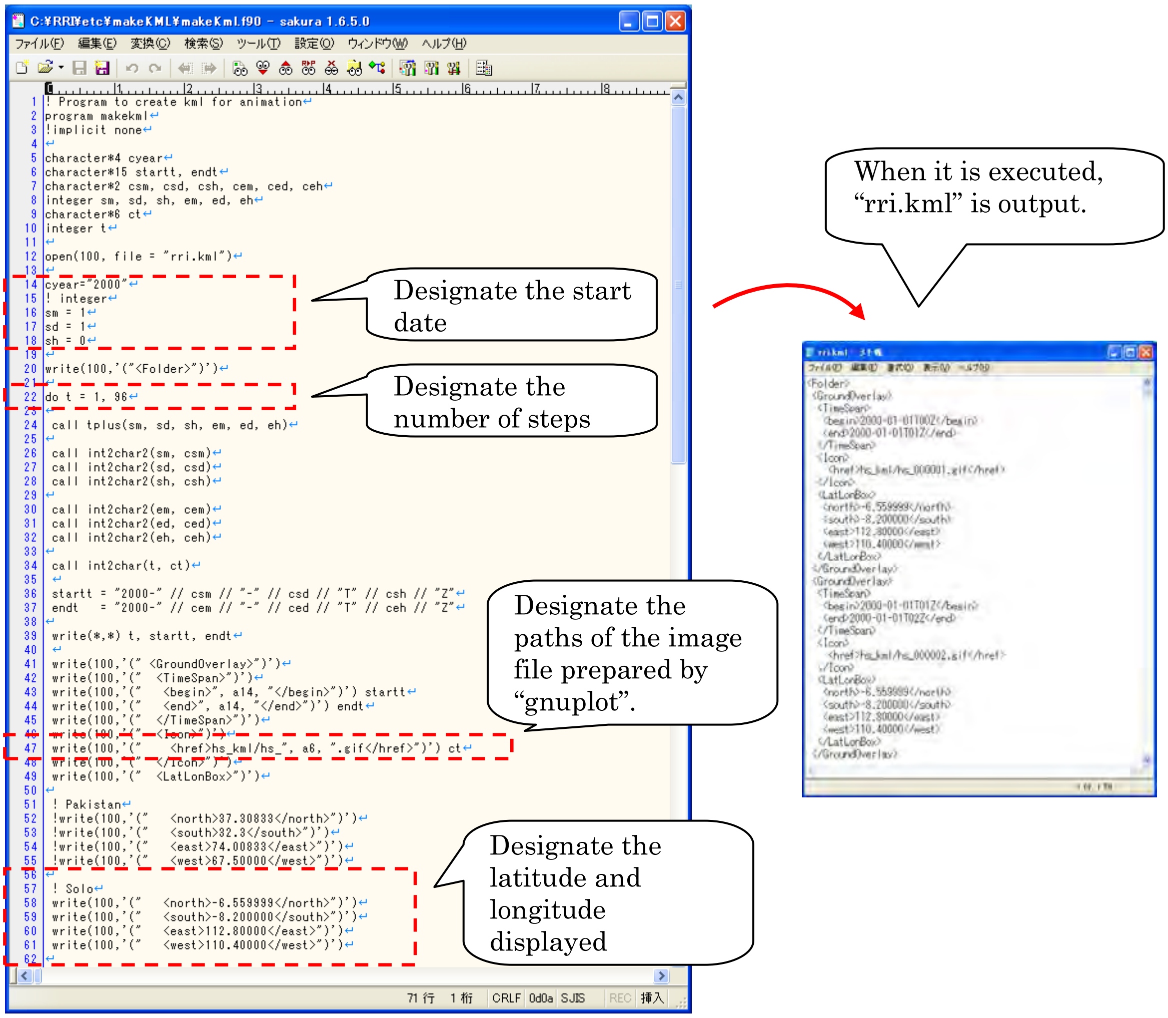
③ Check the created files specified in L4 of “calcPeak.txt”.

④ The obtained peak water data follows ESRI/ASCII format that can be visualized with ArcGIS.

7.5 Displaying Results on Google Earth

7.5.1 Preparing KML File

By using "RRI/etc/makeKML.f90", a kml file (e.g. "rri.kml") can be prepared.

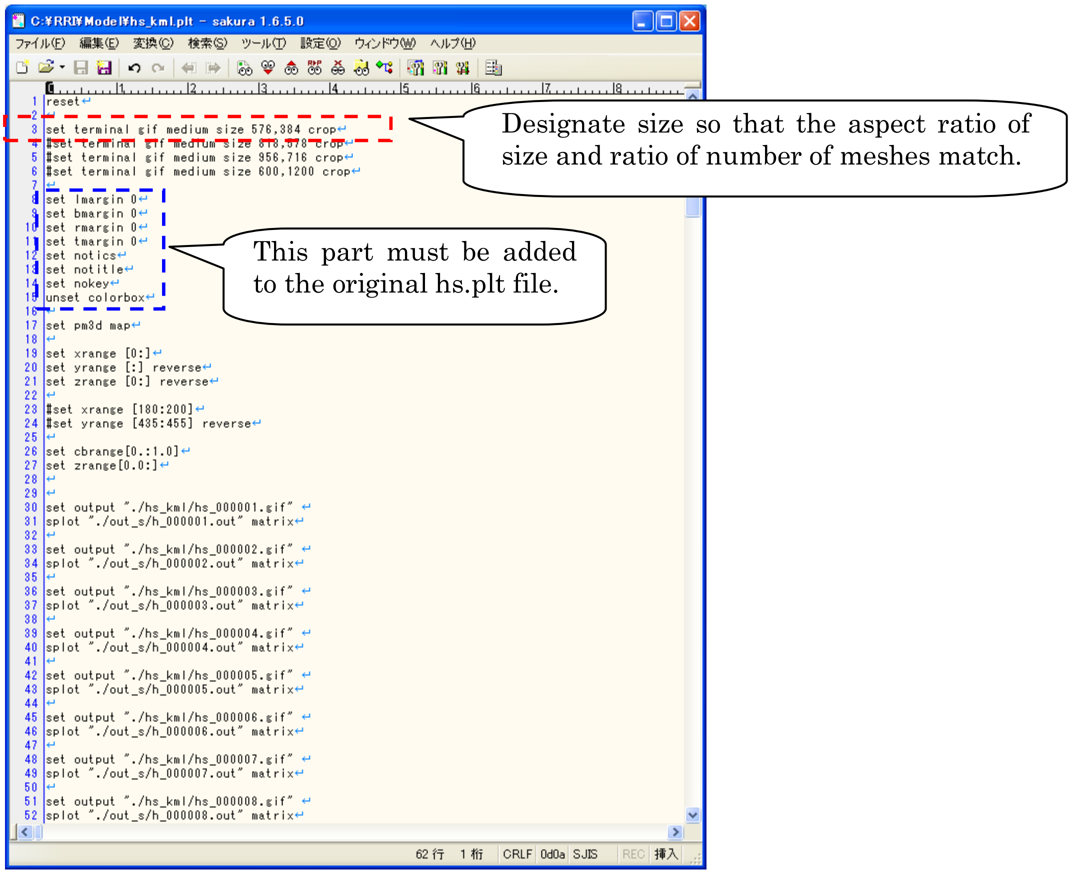


※ The output of "rri.kml" reads gif files created in the folder of "hs_kml".

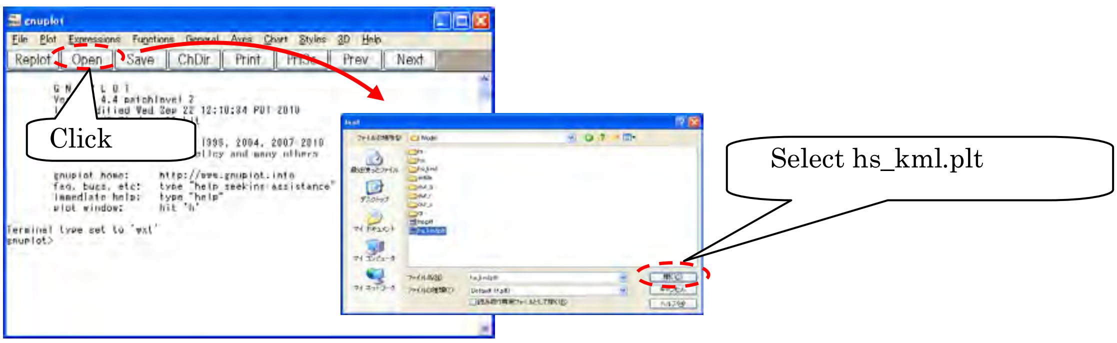
7.5.2 Plotting KML Use Data Using GNUPLOT

The method of plotting "hs_kml.plt" using "gnuplot" is shown below.

① Prepare a gnuplot file (e.g. "RRI/Model/hs_kml.plt"), which can be essentially the same as hs.plt explained above. However, the gnuplot script file used here (i.e. hs_kml.plt) must have some additional statements in the blue box in the following figure. The statements delete unnecessary axis and legends to be appropriately overlay on Google Earth.



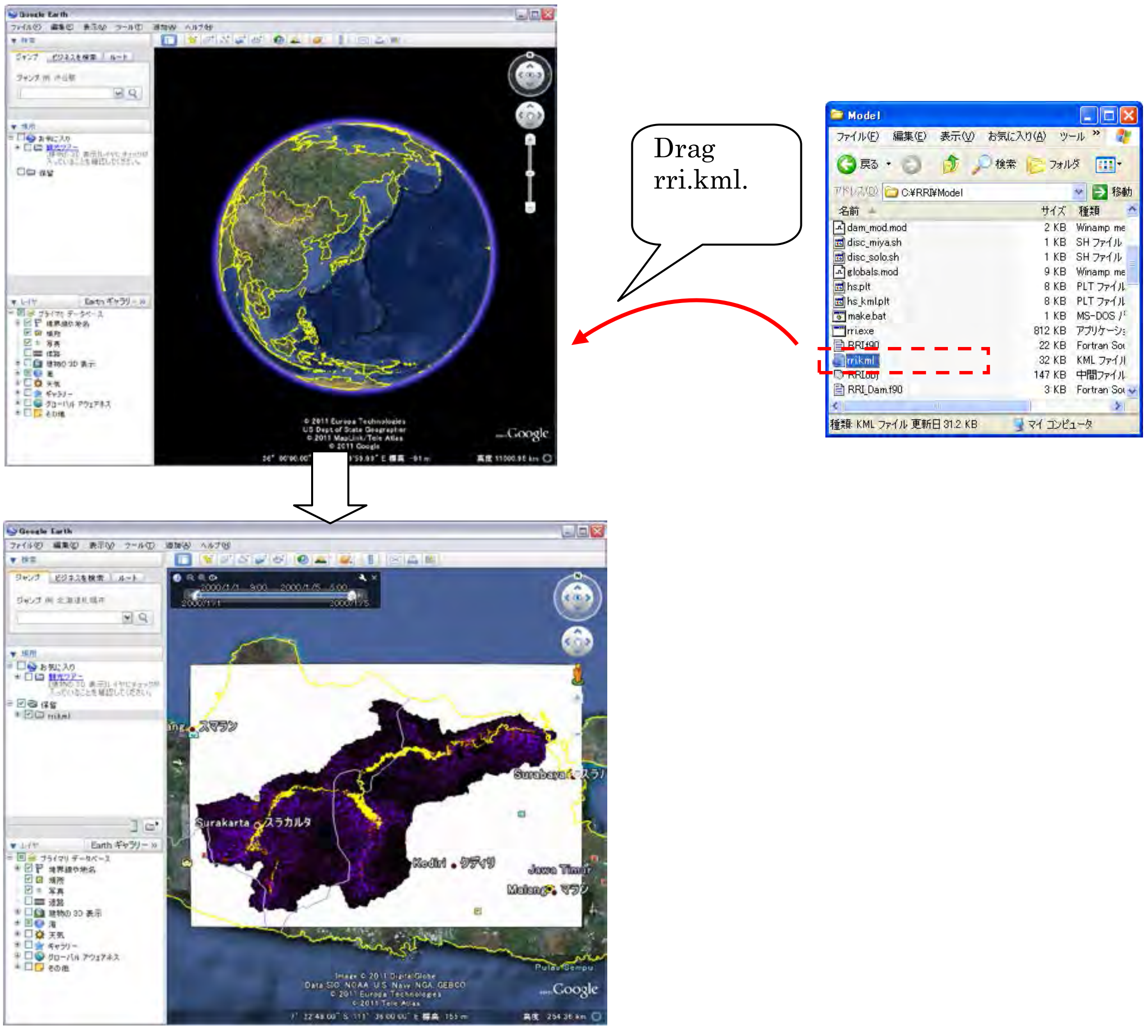
② Start “GNUPLOT” and run “RRI/Model/ hs_kml.plt”.



③ An image file is prepared in the “RRI/Model/hs_kml” folder. (Note that a new folder hs_kml must be created in advance.)

7.5.3 Displaying on Google Earth

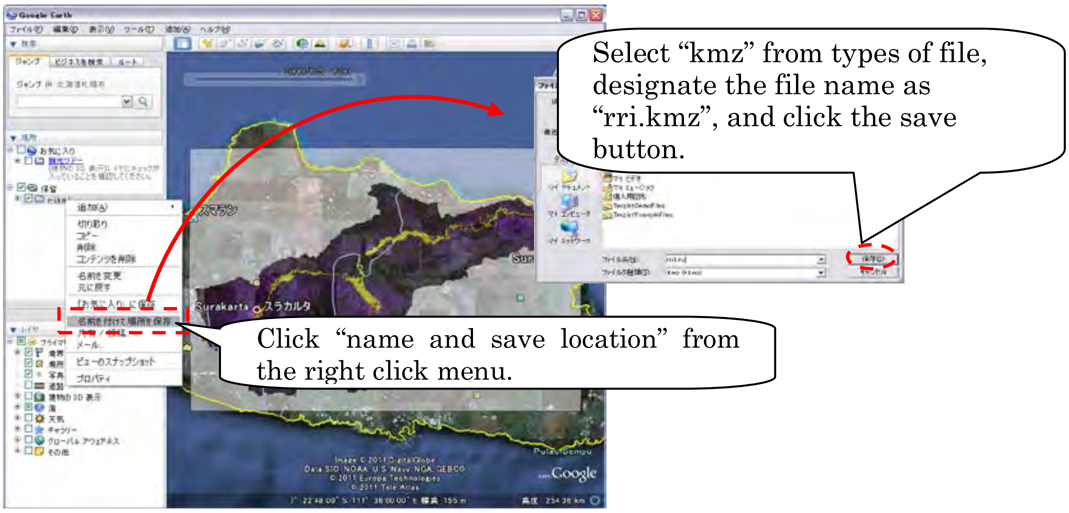
① Start Google Earth and drag “/RRI/Model/rri.kml”.



② Designate permeability rate.

③ Execute animation

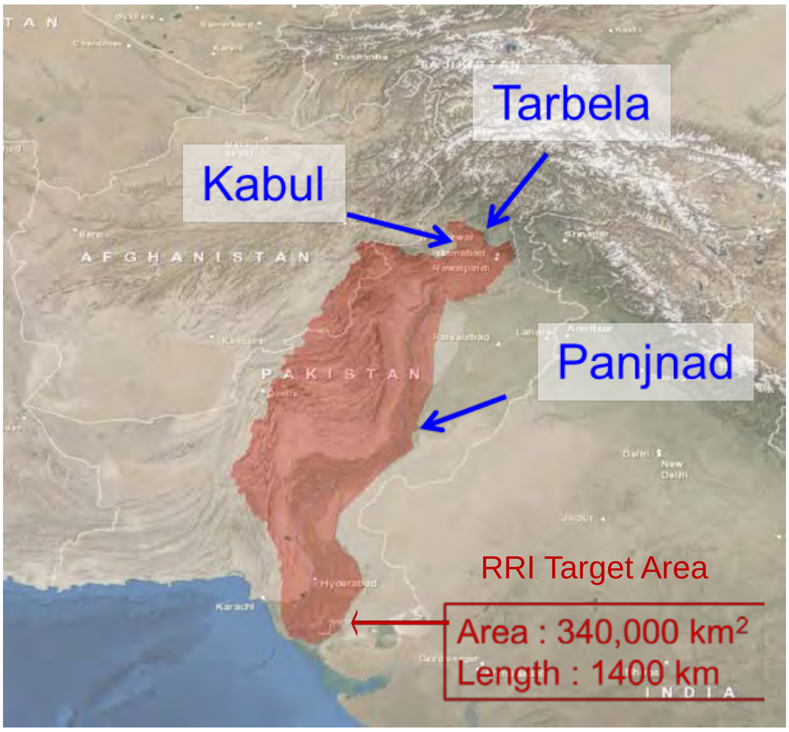
④ Save the kmz file.



※ Image information is included in the "rri.kmz" file, so that it can be distributed to other users without read gif files.

8. Application Example

This section presents the application of RRI Model to the lower Indus River basin. The target area is below Tarbela dam, Kabul and Panjdnad points as indicated below. The simulation domain is about 340,000 km^2 and the river length is about 1,400 km. In this example, the river discharge boundary conditions are prepared based on observed discharge records during 2010 floods to force the model with rainfall records.

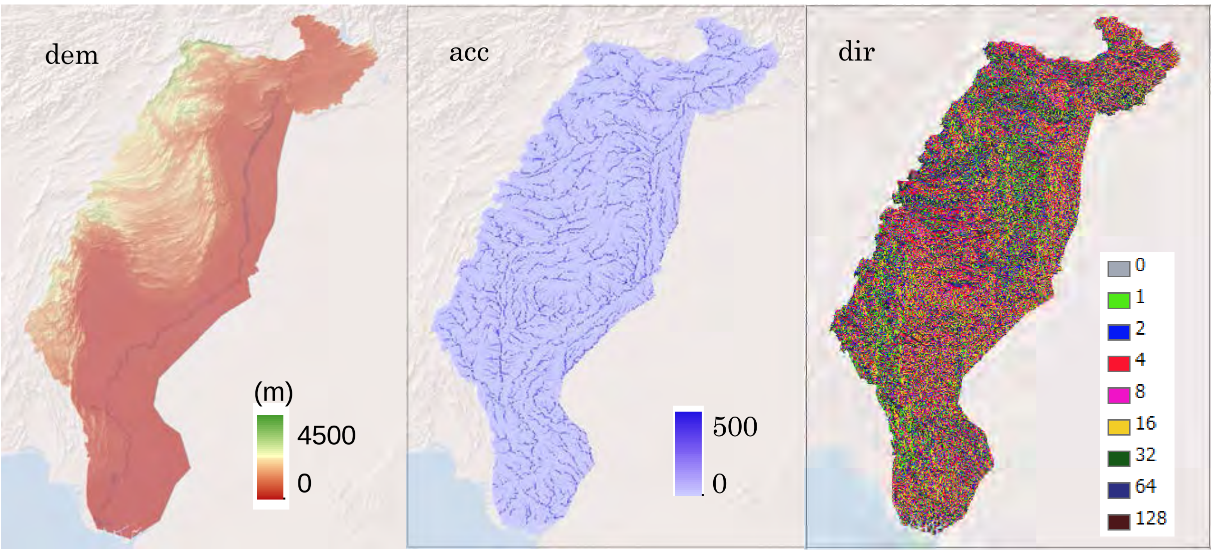


A polygon covering the simulation target (the red mask in the above figure) was prepared first. The flow direction data in HydroSHEDS (30sec) was used to identify the entire Indus River basin. Then the upstream areas above Tarbela, Kabul and Panjnad were removed from the entire Indus River basin.

The background image of the above figure can be obtained from the following site (http://goto.arcgisonline.com/maps/World_Imagery) and used in ArcGIS.

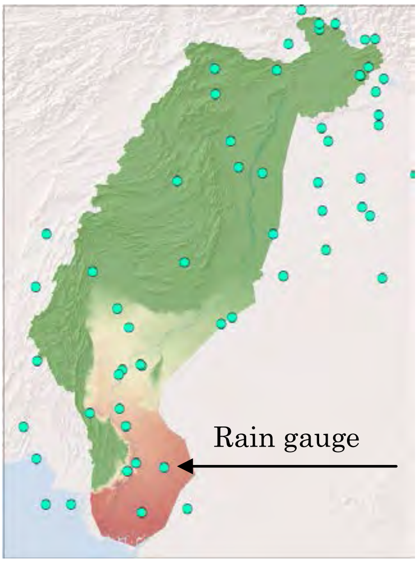
8.1 On Input Topography

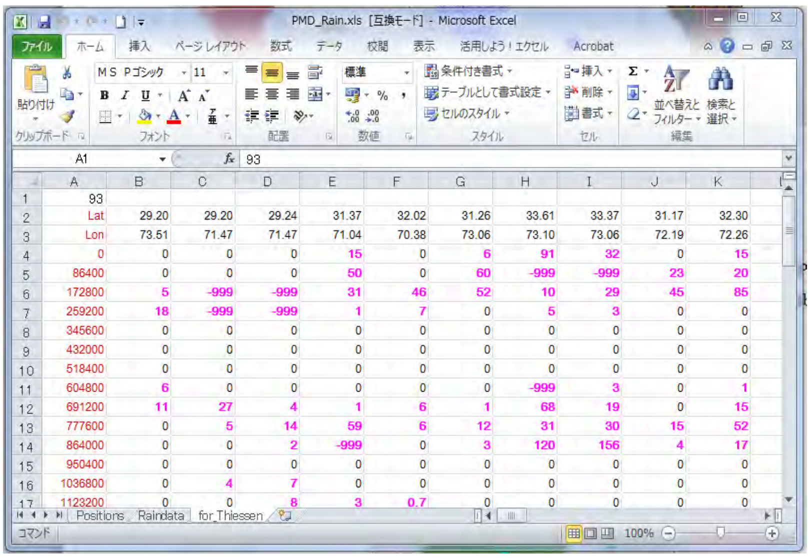
By using the catchment polygon, dem, acc and dir datasets were clipped for the catchment area. The function embedded in ArcGIS ([Spatial Analyst Tools] → [Conditional] → [Con]) was used to mask the target area out of the regional datasets of HydroSHEDS (30 second resolution). Then "demAdjust2" program was used to adjust dem and dir to create adem2 and adir.



8.2 On Input Rainfall

Ground gauged rainfall records provided by Pakistan Meteorological Department (PMD) were used for the simulation. The green dots in the left figure below show their spatial distribution. The below right figure is the formatted ground gauged rainfall data with the latitude and longitude information. Total 93 data was used to create spatially distributed rainfall data.

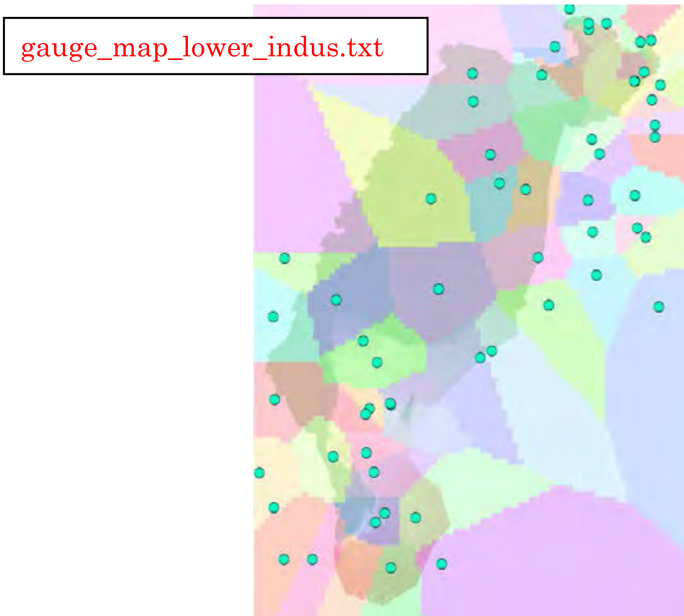




	A	B	C	D	E	F	G	H	I	J	K
1	93										
2	Lat	29.20	29.20	29.24	31.37	32.02	31.26	33.61	33.37	31.17	32.30
3	Lon	73.51	71.47	71.47	71.04	70.38	73.06	73.10	73.06	72.19	72.26
4	0	0	0	0	15	0	6	91	32	0	15
5	86400	0	0	0	50	0	60	-999	-999	23	20
6	172800	5	-999	-999	31	46	52	10	29	45	85
7	259200	18	-999	-999	1	7	0	5	3	0	0
8	345600	0	0	0	0	0	0	0	0	0	0
9	432000	0	0	0	0	0	0	0	0	0	0
10	518400	0	0	0	0	0	0	0	0	0	0
11	604800	6	0	0	0	0	0	-999	3	0	1
12	691200	11	27	4	1	6	1	68	19	0	15
13	777600	0	5	14	59	6	12	31	30	15	52
14	864000	0	0	2	-999	0	3	120	156	4	17
15	950400	0	0	0	0	0	0	0	0	0	0
16	1036800	0	4	7	0	0	0	0	0	0	0
17	1123200	0	0	8	3	0.7	0	0	0	0	0

Note that the first column of the excel sheet represents the time stamp of the rainfall data in second. For example, at the row of 172800 sec, the daily rainfall [mm/d] between time 86400 and 172800 sec was stored. Then all the data was copied to a text editor and save it as ASCII.

The ASCII file is the input data of /etc/rainThiessen program that generates the spatially distributed rainfall data. Note that the "gauge_map_lower_indus.txt" is also created after running /etc/rainThiessen program, so that one can check the spatial representation of each rain gauge (see the figure below after converting from the ASCII to Raster with ArcGIS).

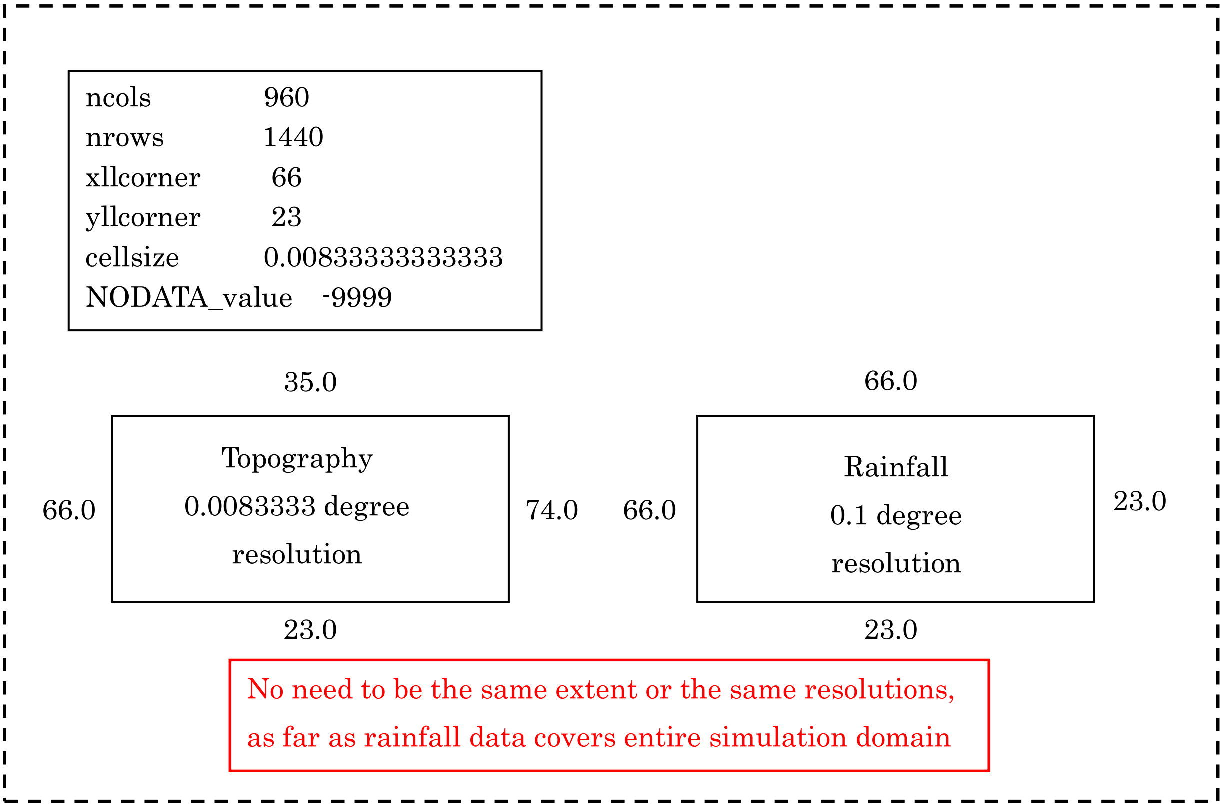


Here is the sample of the rainThiessen program input file (rainThiessen.txt).

rainThiessen.txt

```
./indus/gauge_1d_2010.txt
24
./indus/rain_lower_indus_gauge_2010.dat
./indus/gauge_map_lower_indus.txt
ncols    80
nrows 120
xll 66.0
yll 23.0
cellsize 0.1      → in degree
```

The rainfall data must cover all the simulation domain. However, it is not necesssary to have the same resolution or the same coverage area. For exmaple, 0.1 degree (approx. 10 km) may be fine enough to distribute the ground gauged rainfall for this case. Thus above rainThiessen.txt read by the rainThiessen program specifies the output resolution of 0.1 degree.



RRI_Input.txt

```
RRI_Input_Format_Ver1_3

./infile/lowerindus/rain/rain_lower_indus_gauge_2010.dat
./infile/lowerindus/adem2_lid1k.txt
./infile/lowerindus/acc_lid1k.txt
./infile/lowerindus/adir_lid1k.txt

0           # utm(1) or latlon(0)
1           # 4-direction (0), 8-direction(1)
2568        # lasth
600         # dt
60          # dt_riv
104         # outnum
66.0d0      # xllcorner_rain
23.0d0      # yllcorner_rain
0.1 0.1     # cellsize_rain
```

xllcorner_rain, yllcorner_rain cellsize_rain (x, y) are specified in RRI_Input.txt

8.3 On Input Evapotranspiration

Current version of RRI Model does not have a function to estimate evapotranspiration from climate variables. However, by giving evapotranspiration rate as one of the input files, the model takes the equivalent amount of water from surface and subsurface storages.

The format of the evapotranspiration input is the same as rainfall. Hense the grid cell size and time step of evapotranspiration file can be arbitrary set. For example, to set the constant rate of evapotranspiration, one can prepare the following input file (e.g. evp_4mm.txt), in which the value of 0.166667 mm/h corresponds to 4 mm/d of evapotranspiration.

evp_4mm.txt

```
0 1 1
0.166667
10000000 1 1
0.166667
```

To read the evapotranspiration input file, set flag 1 on the L71 and specify the input file name. The coordinate of south west corner (xllcorner and yllcorner) as well as the cellsize (x and y direction) must be also set in L73-L75.

RRI_Input.txt

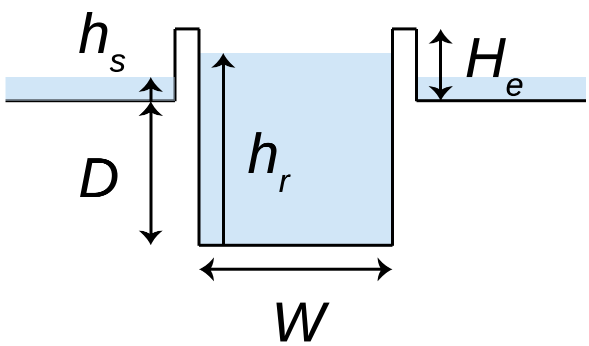
```
L71 | 1
L72 | ./infile/lowerindus/evp_4mm.txt
L73 | 66.0d0               # xllcorner_evp
L74 | 23.0d0               # yllcorner_evp
L75 | 1000.d0 1000.d0      # cellsize_rain
```

xllcorner_evp, yllcorner_evp cellsize_rain (x, y) are specified in RRI_Input.txt

Note that if sufficient water exists on a slope grid cell, and if the grid cell store water in the Green Ampt-Model, the model takes water from the cumulative water in GA model. **If a user wants to avoid the evapotranspiration from the GA model, use flag "2" instead of "1" on L71.**

8.4 On River Channel Geometry Setting

RRI Model assumes the rectangle shape for all river cross sections. To determine river cross sections (incl. width W, depth D and levee height H_e), the following two options are available.



A) Use empirical equations with parameters defined in RRI_Input.txt

B) Read the values from files and specify the files in RRI_Input.txt

RRI_Input.txt

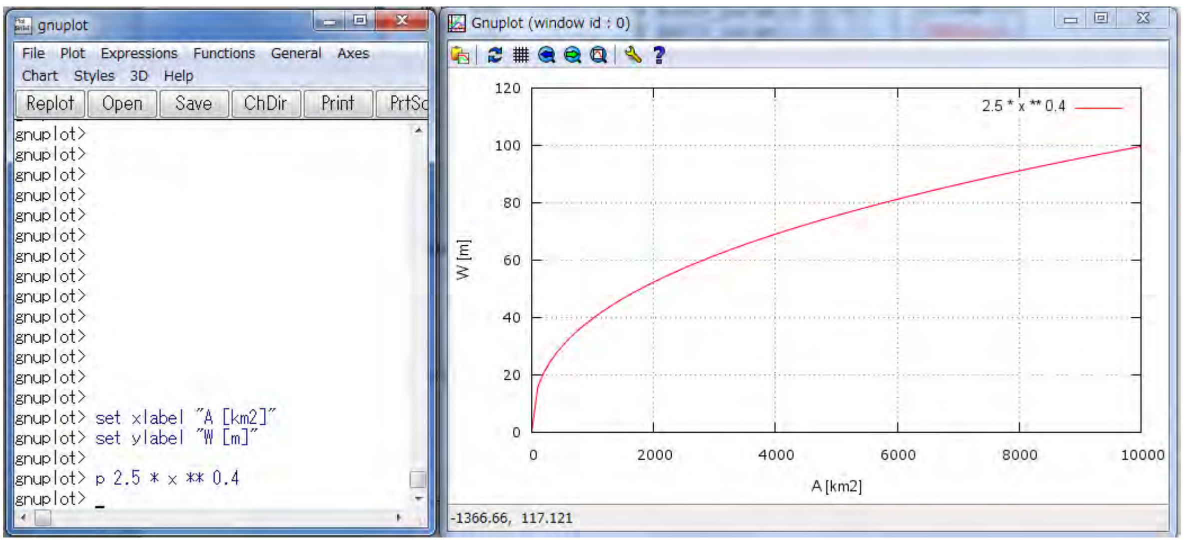
L33	100	# riv_thresh	Option A
L34	2.5d0	# width_param_c	
L35	0.4d0	# width_param_s	
L36	0.1d0	# depth_param_c	
L37	0.4d0	# depth_param_s	
L38	0.d0	# height_param	
L39	20	# height_limit_param	
L40			
L41	1	← 0 : Option A / 1 : Option B (Read from files)	
L42	./infile/lowerindus/width_lid1k.txt		Option B
L43	./infile/ lowerindus /depth_lid1k.txt		
L44	./infile/ lowerindus /height_lid1k.txt		
L45			

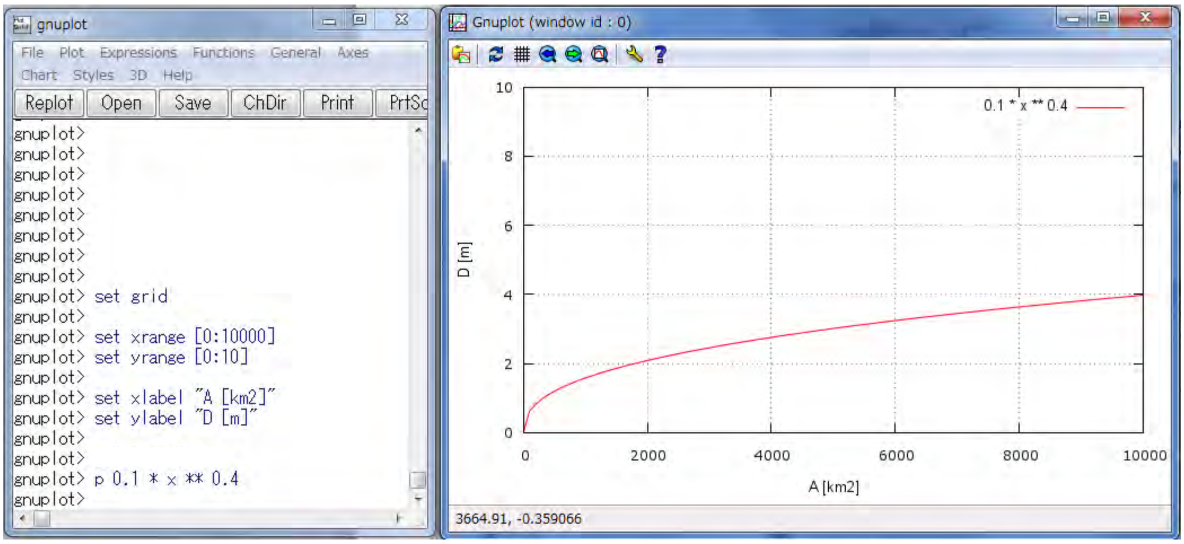
<u>A) For the first option,</u> the parameters of the following empirical equations must be appropriately set to represent target catchment condition (L33 – L39 of RRI_Input.txt).

$$width = c_w A^{s_w}$$

$$depth = c_d A^{s_d}$$

where A in the equations is the upstream catchment area [km²] for each river grid-cell. The unit of width and depth are [m]. The parameter "riv_thresh" defines the threshold of flow accumulation (i.e. number of upstream cells) to distinguish river grid cells or slope grid cells. Recall that for RRI model, slope exists even on a river grid cell.





<u>B) For the second option,</u> a user can prepare three files separately to represent width, depth, and height distributions. All those files must have the same number of row, column and resolution as the topography data (i.e. adem, acc and adir). The format of these data is ArcGIS ASCII format (i.e. the same as the topography data).

Note that the width file (e.g. ./infile/lowerindus/width_lid1k.txt) is used to decide whether each grid-cell has river or not (*width* > 0 is treated as a river grid cell). The values of depths and heights must be appropriately defined on a cell where the *width* > 0.

To support for creating the width, depth and height files, a Fortran program called /etc/makeRiver2/ can be used. The program reads "acc" file to calculate the upstream catchment area A [km^2] for each grid cell and a user can define different equations or fixed values within the program to create the three river cross section files.

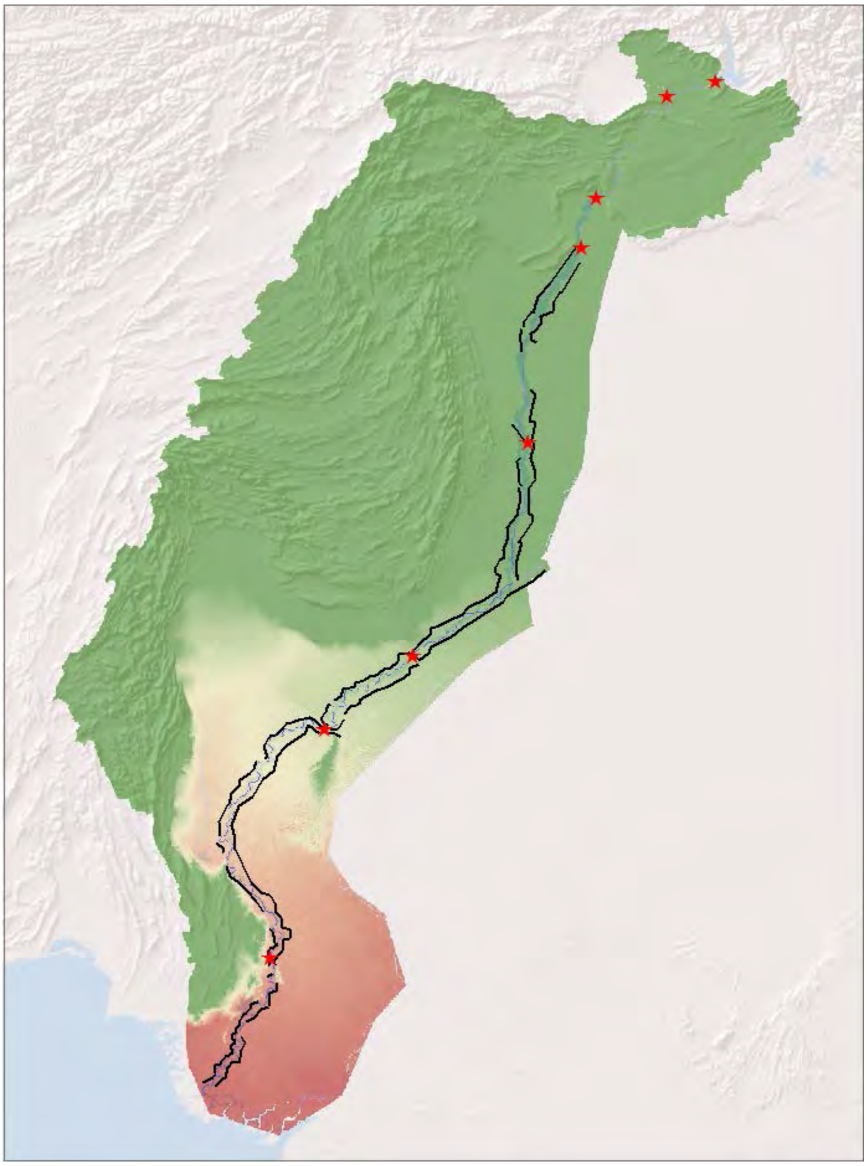
8.5 On Embankment Setting

There are two kinds of embankment settings in RRI simulation.

- A) Embankment along rivers
- B) Embankment on slope grid cells

<u>A) The first type of embankment</u> is illustrated in the figure of a river cross section. The effect of embankment is considered during the interaction of water between river and slope. To include the first type of embankment, the height value (*height* > 0) must be set on river grid cells (*width* > 0). Because of the RRI Model basic structure, a river is set as a centerline of a

slope grid, it is not possible to apply different embankment height for different side of the river for this option.



B) The second type of embankment represents roads, railways or other structures that prevent water to across. Since the embankment along the main Indus River is located a few kilometers apart from the main channel (see above figure), this second type suits better. The location information of the embankment was converted to raster data having the same resolution with topographic data on ArcGIS. The above mentioned "*height*" file specified in RRI_Input.txt can contain the height information (and therefore the embankment location information) on slope grid cells.

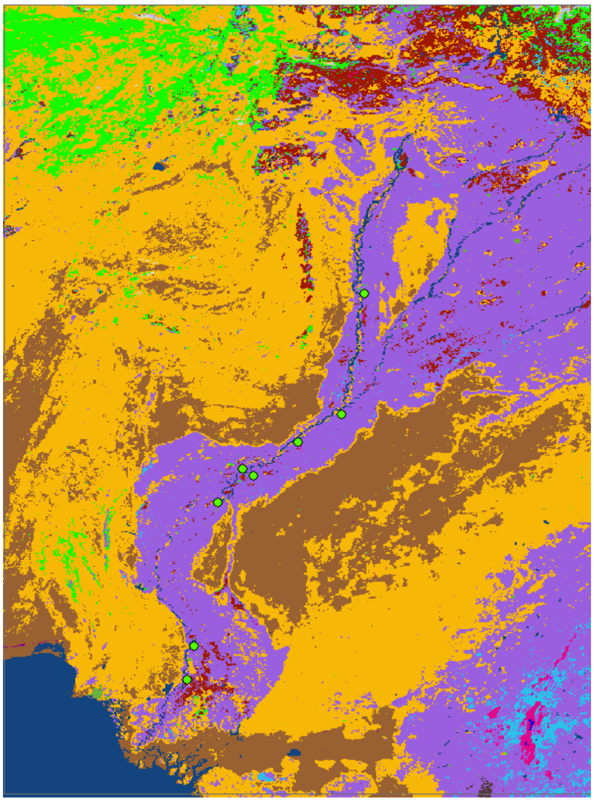
Note that even if a user intends to set a continuous embankment apart from a main river, if a tributary joins into the river and if the "*height*" value is set on a river grid cell where *width* >

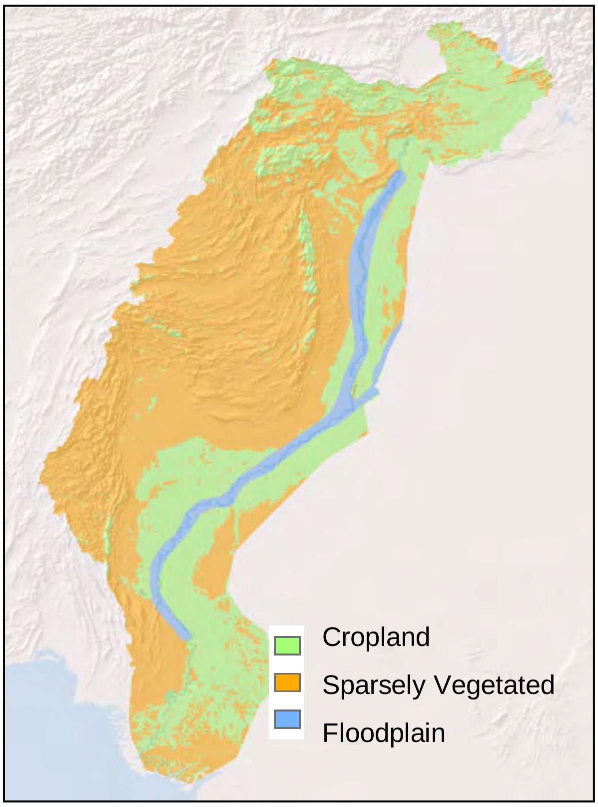
0, the embankment would be regarded as the embankment of Type A. As a result, the set embankment will be discontinuous at the location.

To avoid the situation and elevate DEM even on the tributary (or river grid cells), one can use the flag of "2" on L41.

8.6 On Land Class Setting

The effects of land cover (or soil type) can be reflected by assigning different model parameters. In this example, GLCC-V2 (Global Land Cover Characterization) provided by USGS was used. The original land cover data (left) is too detail to assign all different parameters; therefore, similar land cover types were merged into two categories: Cropland and Sparsely Vegetated, and also overlaid additional Floodplain polygon.





For re-classing the original land cover data, ArcGIS function [Spatial Analyst Tools] → [Reclass] → [Reclass by ASCII File] was used. The following lookup table was prepared by a text editor to define the re-class. Different lookup tables may be defined for different projects. Note that the number of the raster data (in this case 1, 2 and 3) corresponds to the column of parameter sets in RRI_Input.txt. Thus provide sequential numbers starting from 1 for representing different land covers.

Finally the re-classed land cover was converted to the ArcGIS/ASCII format and saved it as "lu_lid1k.txt". Note that the file can be read by RRI Model by indicating the file link in "RRI_Input.txt".

Lookup Table
(Indus Example)

1 : 1
2 : 1
3 : 1
4 : 1
5 : 1
6 : 1
7 : 1
8 : 2
9 : 1
10 : 1
11 : 1
12 : 1
13 : 1
14 : 1
15 : 1
16 : 1
17 : 1
18 : 1
19 : 2
20 : 1
21 : 1
22 : 1
23 : 1
24 : 1
99 : 1
100 : 1

Legend of GLCC-V2

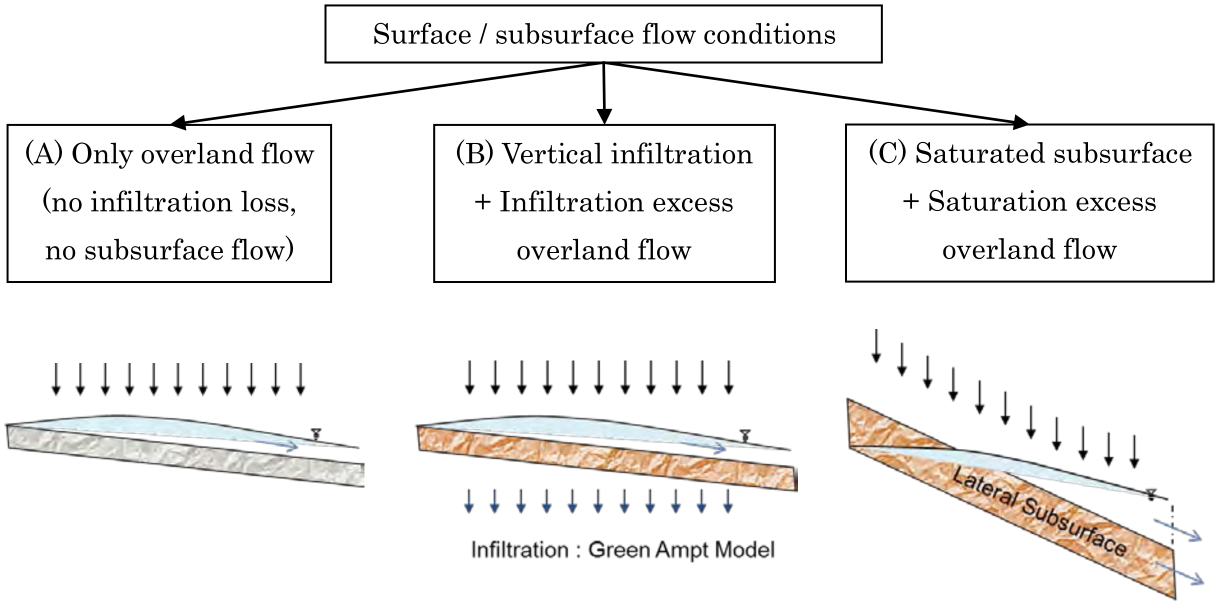
USGS Land Use/Land Cover System Legend (Modified Level 2)

Value	Description
1	Urban and Built-Up Land
2	Dryland Cropland and Pasture
3	Irrigated Cropland and Pasture
4	Mixed Dryland/Irrigated Cropland
5	Cropland/Grassland Mosaic
6	Cropland/Woodland Mosaic
7	Grassland
8	Shrubland
9	Mixed Shrubland/Grassland
10	Savanna
11	Deciduous Broadleaf Forest
12	Deciduous Needleleaf Forest
13	Evergreen Broadleaf Forest
14	Evergreen Needleleaf Forest
15	Mixed Forest
16	Water Bodies
17	Herbaceous Wetland
18	Wooded Wetland
19	Barren or Sparsely Vegetated
20	Herbaceous Tundra
21	Wooded Tundra
22	Mixed Tundra
23	Bare Ground Tundra
24	Snow or Ice
99	Interrupted Areas
100	Missing Data

8.7 On Parameter Setting

Model parameter values are defined in RRI_Input.txt. In this section, the general idea to decide model parameters are described first, then a calibrated model parameter set for the Indus River basin will be shown as an example.

For each land cover class, decide (A), (B) or (C) in the following figure depending on infiltration and subsurface processes, so that the number of calibration parameters will be limited.



Example of parameter values (+ their recommended ranges)

Parameters	Notation	(A)	(B)	(C)
n (Land) ($m^{-1/3}s$)	ns_slope		0.3 (0.15 ~ 1.0)	
n (River) ($m^{-1/3}s$)	ns_river		0.03 (0.015 ~ 0.04)	
d_a (m)	da	0	0	0.4 (0.1 ~ 1.0)
k_a (m)	ka	inactive	inactive	0.1 (0.01 ~ 0.3)
D (m) *	soildepth	1.0	1.0	1.0
k_{sv} (m/s)	ksv	0	5.556d-7	0
$\phi - \theta_i$	delta	inactive	0.471	inactive
S_f	faif	inactive	0.273	inactive
Infilt. Limit (m) * *	infilt_limit	inactive	0.4 (0.1~1.0)	inactive

Note: 0.d0 is used in RRI_Input.txt to represent double precision of 0.0.

For case (A), where only overland flow without infiltration or subsurface flow process are considered, set both da = 0 and ksv = 0.

For case (B), where vertical infiltration + infiltration excess overland flow are considered, set da = 0.

For case (c), where saturated subsurface + saturation excess overland flow are considered, set ksv = 0.

Parameter values in the above table are just one example values (+ approximate ranges).

Note that even though the values in inactive part do not affect the simulation result, a double precision value like 0.0d0 must be filled in RRI_Input.txt (see the sample below).

* "soildepth" parameter is a dummy value as da represents actual soil depth multiplied by effective porosity (see the equation more in detail). Nevertheless, D must be set larger than da.

Parameter values used for the Indus River basin application

Parameters	Notation	*(1) Cropland*	*(2) Sparse Veg.*	*(3) Floodplain*
n (Land) ($m^{-1/3}s$)	ns_slope	0.1	0.1	0.02
n (River) ($m^{-1/3}s$)	ns_river		0.015	
d_a (m)	da	0	0	0
k_a (m)	ka	inactive	inactive	inactive
D (m) *	soildepth	inactive	inactive	inactive
k_{sv} (m/s)	ksv	5.56d-7	6.06d-7	5.56d-7
$\phi - \theta_i$	delta	0.471	0.453	0.471
S_f (m)	faif	0.273	0.1101	0.273
Infilt Limit (m)	infilt_limit	0.25	0.1	0.1

The following figure shows the parameter settings used for the Indus River basin application.

RRI_Input.txt

```
3                     # num_of_landuse
1 1 1                 # diffusion(1) or kinematic(0)
0.0d0 0.0d0 0.0d0          # dm
0.0d0 0.0d0 0.0d0          # da
0.1d0 0.1d0 0.1d0          # ka
4.0d0 4.0d0 4.0d0          # beta
1.0d0 1.0d0 1.0d0          # soildepth
0.15d0 0.15d0 0.15d0       # ns_slope
0.02d0                     # ns_river

5.556d-7 6.056d-7 0.d0     # ksv
0.471d0 0.453d0 0.d0       # delta
0.273d0 0.1101d0 0.d0      # faif
0.25d0 0.0d0 0.d0          # infilt_limit (-1.d0 -> no limit)

```

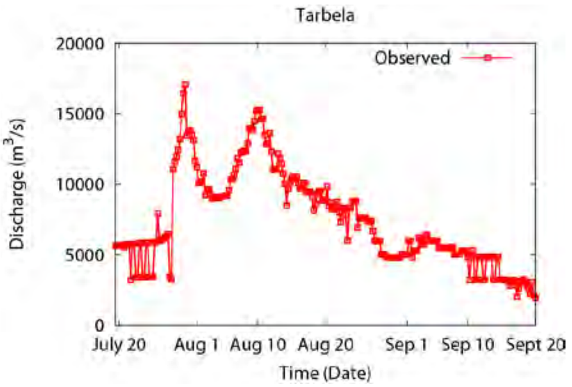
Reference Table : Green-Ampt Infiltration Parameters for different soil texture

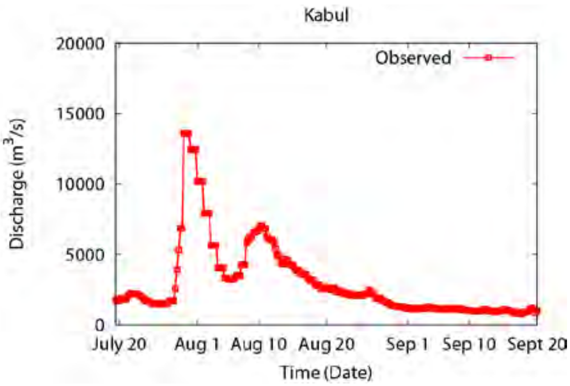
Soil texture class	k_{sv} (m/s)	ϕ	S_f (m)
Sand	6.54E-05	0.437	0.0495
Loamy sand	1.66E-05	0.437	0.0613
Sandy loam	6.06E-06	0.453	0.1101
Loam	3.67E-06	0.463	0.0889
Silt loam	1.89E-06	0.501	0.1668
Sandy clay loam	8.33E-07	0.398	0.2185
Clay loam	5.56E-07	0.464	0.2088
Silty clay loam	5.56E-07	0.471	0.273
Sandy clay	3.33E-07	0.43	0.239
Silty clay	2.78E-07	0.479	0.2922
Clay	1.67E-07	0.475	0.3163

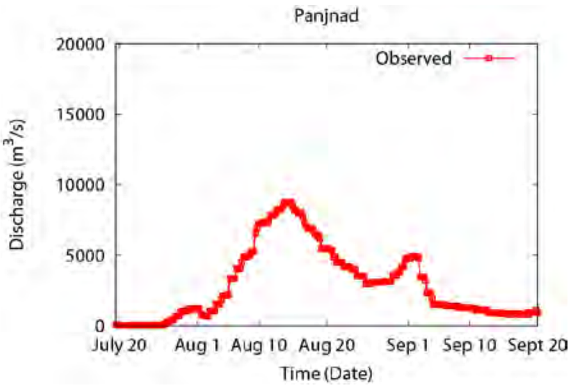
From Rawls, W.J. et al.., 1992. Infiltration and soil water movement. In: Handbook of hydrology. New York: McGrow-Hill Inc., 5.1–5.51. (Units are conveted for RRI Model)

8.8 On Boundary Condition

The following river boundary conditions were set based on the observed discharges at the three locations during the 2010 flood.





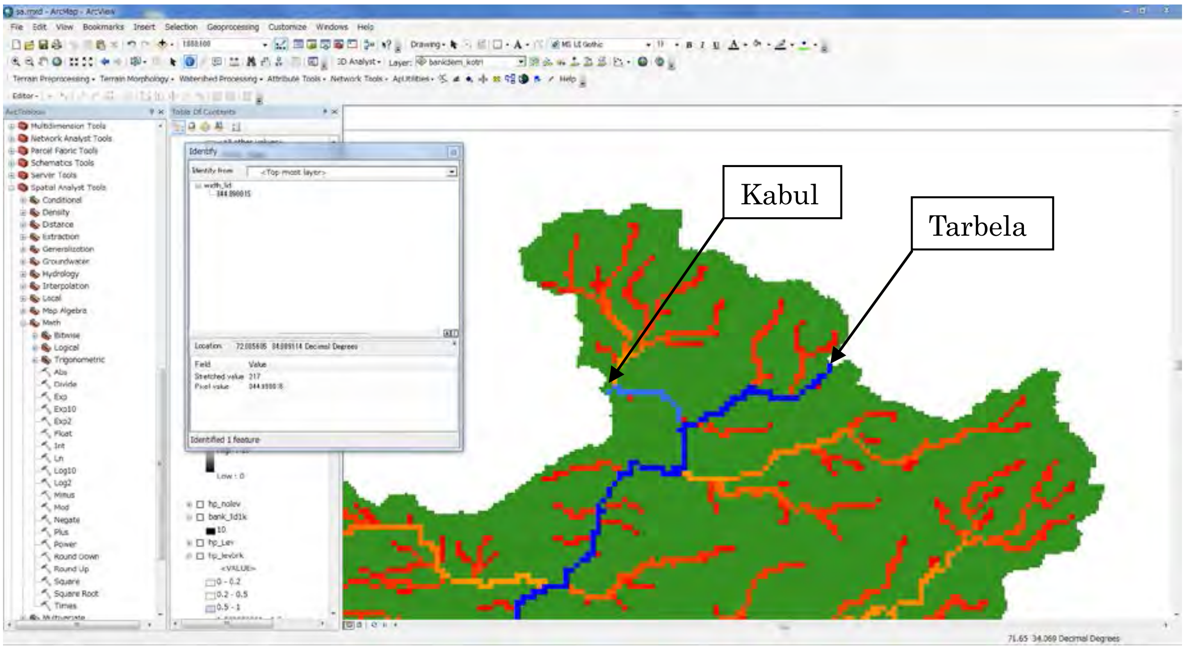


The steps to set river discharge boundary conditions are described below.

① Find locations to provide the boundary conditions.

Viewing acc values on ArcGIS can help you to identify appropriate position with lat lon information along a river channel. Use i (identify) icon to find out the coordinate.

Then use the "/etc/coordinate.xls" to convert from the lat lon coordinate to loc_i and loc_j. See Section 7.3 on the conversion in detail.



② Prepare the following "setBound.txt" as the input file to "/RRI/etc/setBound" program, which creates the input boundary conditon file (e.g. ./disc_lid1k_2010.txt).

setBound.txt

```
../../Model/infile/lowerindus/adem_lid1k.txt
../../Model/infile/lowerindus/acc_lid1k.txt
../../Model/infile/lowerindus/adir_lid1k.txt
./infile/lowerindus/disc_Constant.txt
../../Model/infile/lowerindus/disc_lid1k_Constant.txt
3
119 719
110 803
680 602
```

In the above example of "setBound.txt", L1 to L3 are the paths to the topography files (dem, acc and dir). L4 is the 1D discharge file (input) prepared above and the L5 is the output of the setBound program. L6 indicates the number of points to give the boundary conditions, followed by the positions in loc_i and loc_j.

The created boundary condition files have the same format as the rainfall file. However, unlike rainfall files, the number of columns and rows must be exactly the same as the topography data, so that RRI Model knows where to give the boundary.

Note that discharge boundary conditions including along river and on slope must have the information of the directions. In other words, they should be vector values rather than the scalar values. To decide the direction of the discharge boundary conditions, RRI Model refers to the flow direction in "dir" file.

③ Settings in RRI_Input.txt

After preparing the boundary conditon file (e.g. disc_lid1k_2010.txt) and move the file in the appropriate folder (e.g ./infile/lowerindus/), edit the RRI_Input.txt file as follows.

RRI_Input.txt

```
L46  0.d0                 # init_cond_slo
L47  0.d0                 # init_cond_riv
L48
L49  0 0 0
L50  ./infile/hs_init_dummy.out
L51  ./infile/lowerindus/hr_init_lid1k.txt
L52  ./infile/gampt_ff_init_dummy.out
L53
L54  0 0
L55  ./infile/wlev_bound_dummy.txt
L56  ./infile/hr_bound_dummy.txt
L57
L58  0 1
L59  ./infile/qs_bound_dummy.txt
L60  ./infile/lowerindus/bounds/bound_lid_2010.txt
```

Write the file name of river discharge boundary

Note that water level boundary conditions on slope and/or river can be also set by changing the value on L54 to 1 and specitying the boundary condition file name. The file format is the same as the river discharge boundary condion.

New option to give 1D boundary condition data

The problem of above mentioned approach is that boundary condition files tend to be huge. To avoid the issue, the following option is available from ver. 1.3.2 of RRI Model. In this option, a user can prepare 1D dimensional file (i.e. time series data listed only at boundary locations).

Here is the procedure:

① Find locations to provide the boundary conditions (use coordinate.xls).

② Prepare a 1D boundary condition file with the following format.

setBound.txt

The number of boundary condition setting points

The loc_i and loc_j of all points to give boundary conditions

```
3
lat     110          119          680
lon     803          719          602
0       3936.041733  3007.249151  917.4658428
21600   3936.041733  3007.249151  917.4658428
43200   3936.041733  3007.249151  917.4658428
64800   3879.408039  3044.061053  917.4658428
86400   4813.86399   3015.744206  917.4658428
108000  4700.596602  2944.952088  917.4658428
129600  4842.180837  2899.645133  917.4658428
151200  4672.279755  2922.29861   1093.030294
.....   .....        ....         ....
```

Time series of the boundary condition data (units: [m3/s] for river discharge, and [m] for water depth)

③ **IMPORTANT: Use "2" for the flag on L54 (for water depth) or L58 (for discharge) in RRI_Input.txt, so that RRI program recognizes the boundary condition files are prepared in the above 1D format.**

8.9 On Initial Condition

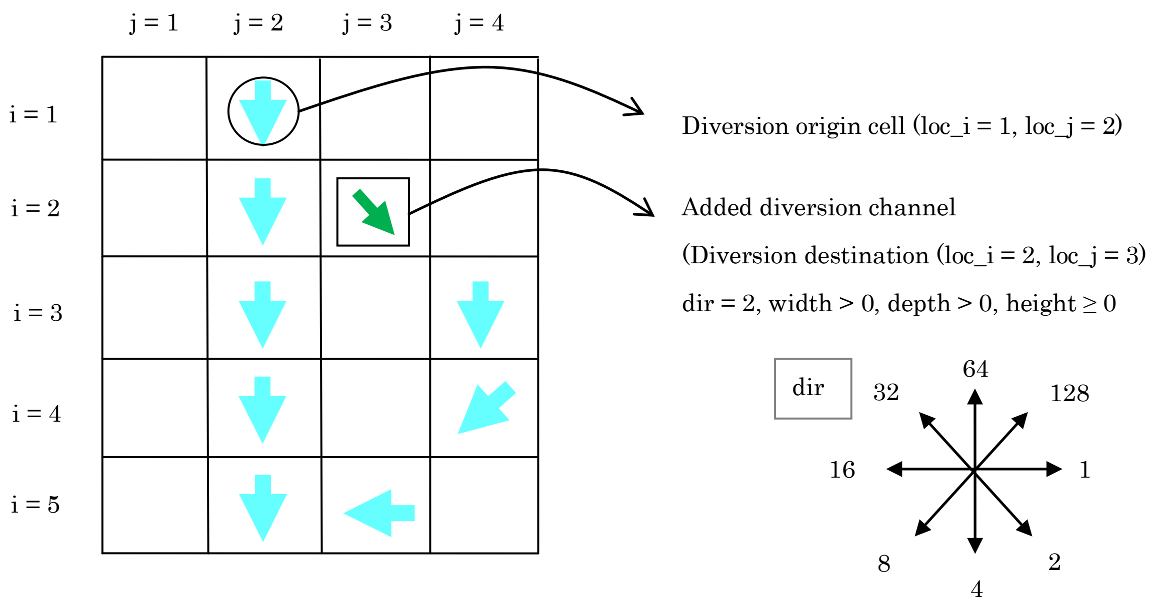
RRI Model can take initial conditions for water depths on slope and river as well as the cumulative water depth in the Green-Ampt model. The format of the files is the same as the output of those variables, so that one can use the output of the RRI as the input for the next simulation.

This feature enables the continuous long-term simulation. In order to read the initial conditions, L49 to L52 in the RRI_Input.txt must be edited in a same manner as the example of the boundary condition setting.

8.10 Diversion option (for advanced users)

RRI model can simulate the effect of diversion in a simple way. The portion of the diversion from a main channel to a diversion channel must be pre-defined by a model user and described in RRI_Div.f90 program. The followings are the basic steps to activate the option.

① Edit input river cross section files (i.e. width, depth, height) and flow direction files to add necessary diversion channels (e.g green arrow for the below figure).



② Check a origin cell (loc_i_org, loc_j_org) and a destination cell (loc_i_dest, loc_j_dest). Both the origin and destination cells must be specified on river grid-cells. Typically these two are adjacent, but not necessary (i.e. diverted water can jump into an apart cell).

③ Prepare a file to specify the origin and destination cells based on the following format. One can list up multiple lines if more than one diversion should be considered.

```
1    2    2    3
loc_i_org   loc_j_org   loc_i_dest   loc_j_dest
```

div_sample.txt

④ Edit "RRI_Div.f90" source code. The simplest way is to decide a ratio to divert from a main channel to a diversion channel. Be sure to recompile the program once the souce code is modified. The part of "RRI_Div.f90" program that users may edit is as follows.

RRI_Div.f90

```
do l = 1, div_id_max
 k = div_org_idx(l)
 kk = down_riv_idx(k)
 kk_div = div_dest_idx(l)
 if( l.eq.1 ) then
  if( qr_idx(k) .gt. 0.d0 ) then
   qr_div_idx(k) = qr_idx(k) * 0.1
   qr_idx(k) = qr_idx(k) - qr_div_idx(k)
  endif
 endif
enddo
```

In this program, the variable "div_id_max" is defined automatically as the number of the diversions (i.e. the number of lines in "div_sample.txt"). Users need to edit the above blue lines to define the portion (or other rule) for each diversion. Add another set of lines for another diversion started with if (l.eq.2) etc. For the above example, 10% of flow from the main stream at (loc_i = 1, loc_j = 2) is diverted to the stream at (loc_i = 2, loc_j = 3).

⑤ Activate this option by setting flag 1 on L70 and specify the diversion file name on L71 in RRI_Input.txt.

8.11 Dam option (for advanced users)

RRI model can simulate the effect of dam reservoirs in a simple way. The dam model has two parameters: outflow discharge and maximum storage volume. The model takes storage volume as a state variable, which continues being updated based on simulated inflow and outflow. The outflow is maintained at a certain discharge rate that is lower than the inflow rate until the storage volume reaches the dam's maximum storage level. After the storage volume exceeds the maximum level, the model is designed to release the water at the same rate as the inflow rate. The parameters must be determined based on dam operation records. The followings are the basic steps to activate the dam model.

① Prepare a dam parmmeter file by the following format.

dam_sample.txt

```
2
Bhumibol    166    71     5800000000    150
Sirikit     135    166    3510000000    500
```

dam names, loc_i_dam, loc_j_dam, storage volume [m^3], constant discharge [m^3/s]

② Activate the dam model by setting flag 1 on L65 and specify the dam file name on L66 in RRI_Input.txt.

添付資料 -2　ワークショップ資料

2013 年 9 月 23 日、24 日に開催

（改良版：配布資料に補足情報を追加）

JICA Meeting Material
23-24 Sep 2013 JST

Technical Workshop on RRI Model		
Target Persons:	Hydrologist belong to RID/DWR (approx. 10persons)	
Purpose	Promotion of innovative hydrological analysis model released by ICHARM, Japan. This work shop shall prove the validity of this model and JST encourages Thai-side to be familiar with the model and utilize for river management plan etc.	
Outline of Workshop		
Day 1		
10:00 - 15:00	A. Outline of RRI Model	
	A-1)	What's the RRI? RRI is one of a distributed hydrological model which has been developed mainly by Dr. Sayama, ICHRM researcher. The why and how this model is developed shall be explained.
	A-2)	Runoff/Inundation analysis 1) What's runoff analysis? To calculate/estimate when (time) and how (water volume) the fallen rainfall flow into the river? Outline of runoff model ➢ Runoff process (surface flow, middle flow and underground seepage etc.) ➢ Short/Long term runoff ➢ Typical runoff models ➢ Concentrated/Distributed hydrological model ➢ Advantages/Disadvantages on each runoff model 2) What's inundation model? ➢ Inundation type (overflow flooding, inland flooding etc.) ➢ Typical inundation model ➢ Difference of overflow type and inland type 3) Issues on runoff/inundation analysis Actually, it is easy to build runoff/inundation model in Japan, because … ➢ Flood term is short (from a few hours to a few days) ➢ Runoff is dominated by surface flow and fast mid-flow. ➢ Influences of storage function in river basin are small and inundation area is regulated landform patterns. Then, how about Chao Phraya River and Mekong River? (Those rivers have far-reaching low land and huge river basins) ➢ Flood term is long, seepage and evaporation are important to calculate runoff correctly. ➢ Runoff is dominated not only surface/fast mid-flow also slow mid-flow and groundwater. ➢ Influence of storage function in low land area is big. RRI model could clear above issues!

	A-3)	Advantages of RRI Model ➢ RRI is able to express runoff processes as faithfully as possible (due to distributed model). ➢ RRI calculate overflow flooding and inland flooding at the same time. ➢ RRI calculate long term runoff since it can estimate groundwater flow.
	A-4)	Future outlook 1) Considering of river cross section RRI M/P version can consider actual river cross sections. However, the input number of cross section depends on the size of calculation grid. 2) Diversion of tributaries/canals At the present, diversion flow is divided with diversion ratio. Diversion flow should be calculated with motion equation 3) Structures (weirs and water gate etc.) At the present, RRI have no structure model
	A-5)	Others 1) IFAS release by ICHARM IFAS is also distributed hydrological model, without inundation module. 2) Differences of RRI FRICS Version
	B. Introduction of the result of M/P study with RRI Model	
	B-1)	Re-production calculation of 2011yr flood
	B-2)	Result of SCWRM M/P
	B-3)	Result of Combination-1 and 2 proposed by Jica Study Team
	B-4)	Findings and conclusions
Day 2		
10:00 – 15:00	C. Practice of RRI Model (Calculation of RRI Model with sample river)	
	C-1)	Necessary Data for RRI Model
	C-2)	Sample Data for RRI Model
	C-3)	Preparing Input Topography Data
	C-4)	Preparing Input Rainfall Data
	C-5)	Execute RRI
	C-6)	View the Results
	C-7)	Try Input Boundary Data
	D. How to get the RRI Model	
	D-1)	Procurement of RRI programs (coded with Fortran 90/95)
	D-2)	About technical support

■ Presentation
■ Practice

ワークショップ風景

ATTENDEES LIST
RRI Model Workshop
Project for the Comprehensive Flood Management Plan
For the Chao Phraya River Basin

Date: September 23, 2013
Location: Meeting Room of Loan Project Office

[THAI SIDE]

No	Name-Surname	Title	Office	Organization
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2	Mr. Chanin Songchon	Civil Engineer	Project Management	RID
3	Mr. Wirunrote Chaisamid	Civil Engineer	Project Management	RID
4	Ms. Kanjanawan Nilklud (Representative)	Hydrologist	Hydrology	RID
5	Ms. Umplika Wonganu	Civil Works Technician Experienced Level	Water Crisis Prevention Center	DWR
6	Mr. Worawat Suwaqnnabud	Civil Engineering Practitioner Level	Water Crisis Prevention Center	DWR
7	Mr. Suriya Srisinthorn	Policy and Plan Analyst	Water Crisis Prevention Center	DWR
8	Ms. Ratikarn Paptib	Hydrologist, Practitioner Level	Bureau of Research Development and Hydrology	DWR
9	Ms. Anchalee Penghuaro	Policy and Planning	Water Policy and Planning	DWR
10	Mr. Pongsak Nunua	Policy and Planning	Water Policy and Planning	DWR

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2	Mr. Kazuhiro NAKAMURA	JICA Study Team Component 1-2
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4	Mr. Daisuke FUJITA	JICA Study Team Component 1-2
5	Ms. Akira WATANABE	JICA Study Team Component 1-2
6	Mr. Peerasak Chantngarm	Interpreter
7	Mr. Chuchat Suwut	JICA Study Team Component 1-2
8	Ms. Kamolnit Ariyakamolpat	JICA Study Team Component 1-2

ATTENDEES LIST
RRI Model Workshop
Project for the Comprehensive Flood Management Plan
For the Chao Phraya River Basin

Date: September 24, 2013
Location: Meeting Room of Loan Project Office

[THAI SIDE]

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4	Mr. Worawat Suwaqnnabud	Civil Engineering Practitioner Level	Water Crisis Prevention Center	DWR
5	Mr. Suriya Srisinthorn	Policy and Plan Analyst	Water Crisis Prevention Center	DWR
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[Observer]

No	Name-Surname	Title	Office	Organization
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6	Mr. Peerasak Chantngarm	Interpreter
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PROJECT FOR THE COMPREHENSIVE FLOOD MANAGEMENT PLAN FOR THE CHAO PHRAYA RIVER BASIN

Technical Workshop on RRI Model

DD:MM:YYYY

JICA Study Team

Purpose of the Workshop

RRI Model has developed by ICHARM[1)], Japan.
This model is employed for the flood forecasting system for lower Chao Phraya River Basin developed by FRICS[2)] (compornent-3), which has already proved the benefits of RRI Model.

In this workshop, the explanation on RRI shall be provided to Thai-side. Through the workshop, we would like you to be familiar with RRI Model and hope you utilize it for effective river management in Thailand.

1) ICHARM: **I**nternational **C**entre for **H**azard **A**nd **R**isk **M**anagement
http://www.icharm.pwri.go.jp/index.html
2) FRICS: **F**oundation of **R**iver & Basin **I**ntegrated **C**ommunications, JAPAN
http://www.river.or.jp/

Contents of Workshop

Day 1st

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A-1) What is RRI Model? P4
A-2) Miscellaneous Knowledge on Runoff/Inundation Analysis P5
A-3) Issues on Runoff/Inundation Analysis P16
A-4) Advantages of RRI Model P19
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D-2) About Technical Support P92

A. Outline of RRI Model

A-1) What is RRI Model ?

Main features/topics about RRI Model are …

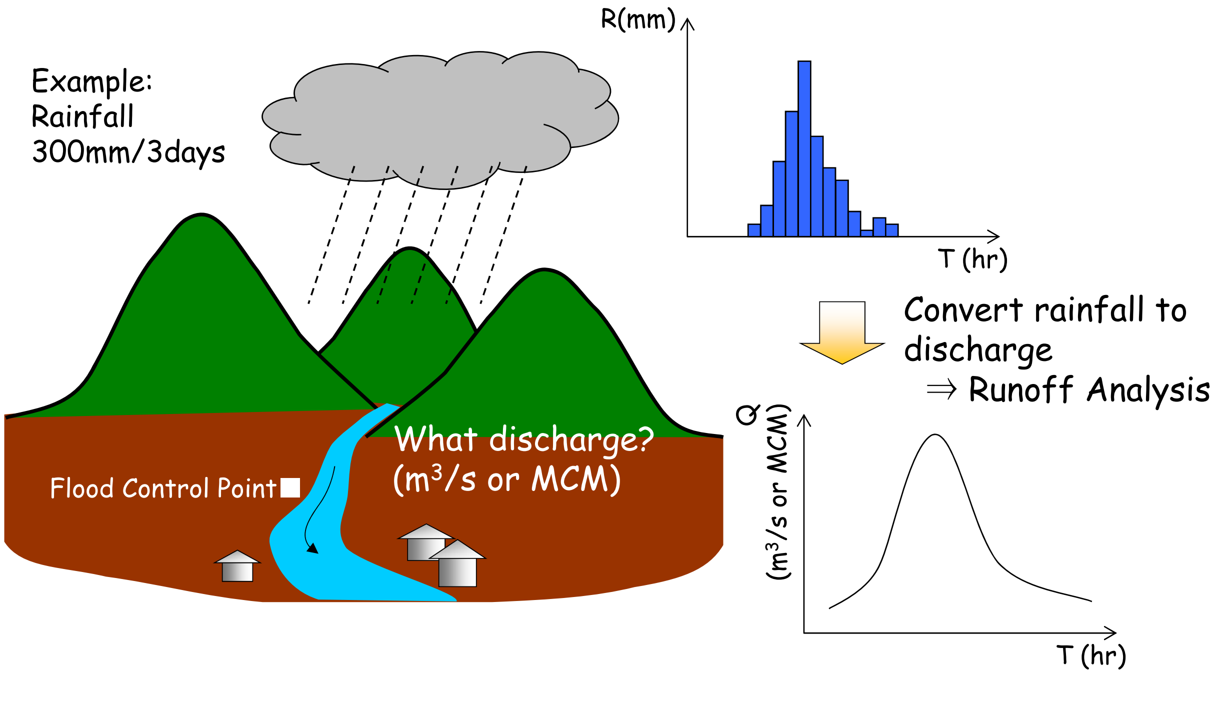
- **RRI** is short for **R**ainfall-**R**unoff-**I**nundation.
- RRI is the distributed hydrological model which has developed by ICHRAM and Dr. Sayama, ICHRAM researcher, has mainly developed this model.
- This model calculates runoff from river basins to rivers/canals considering flood inundation (storage function) and underground seepage.
- This model can be built with only **DEM** (**D**igital **E**levation **M**odel) and local rainfall data.

A. Outline of RRI Model

A-2) Miscellaneous knowledge on Runoff/Inundation Analysis

1) What is runoff analysis?

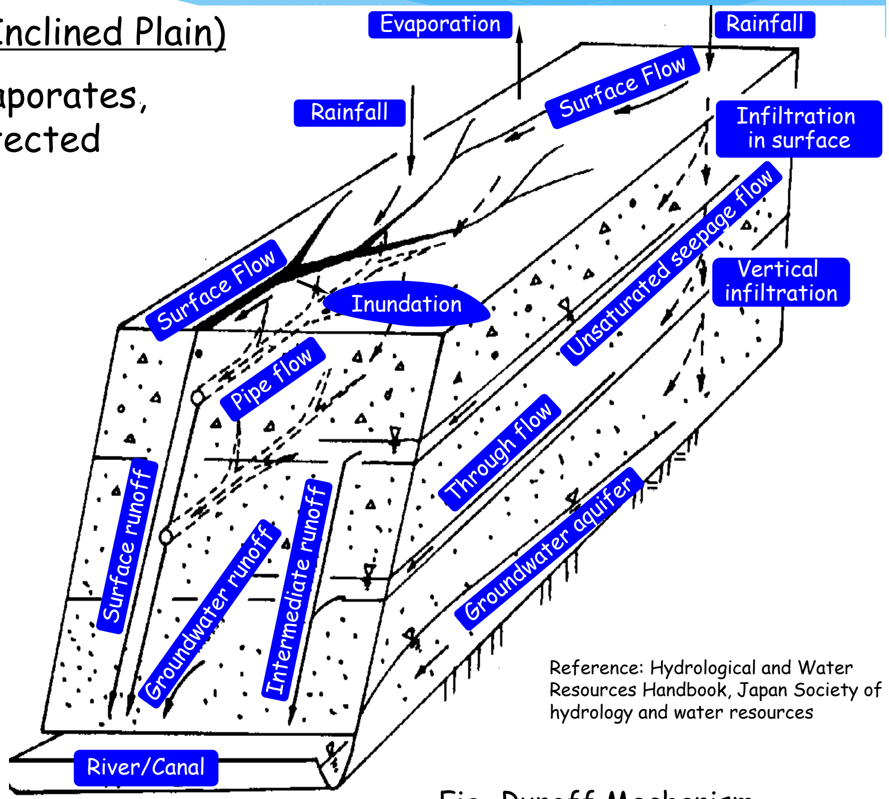
To estimate discharge at arbitrary point with hydrological model



A. Outline of RRI Model

Runoff Mechanism (Inclined Plain)

A part of rainfall evaporates, and inundates in protected land.



Reference: Hydrological and Water Resources Handbook, Japan Society of hydrology and water resources

Fig- Runoff Mechanism

A. Outline of RRI Model

Component of River Flow

Basically, river flow consists of several runoff such as…

- ✓ rainfall in river surface (small influence on river volume)
- ✓ surface runoff (influenced by land use and landscape etc.)
- ✓ fast-intermediate runoff (current in porous surface layer)
- ✓ slow-intermediate runoff (horizontal current in faults and/or crevices)
- ✓ groundwater runoff (= base flow of the river)

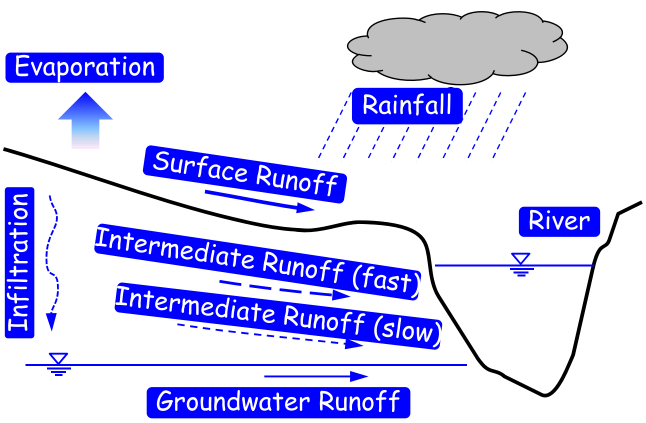


Fig- Runoff Component

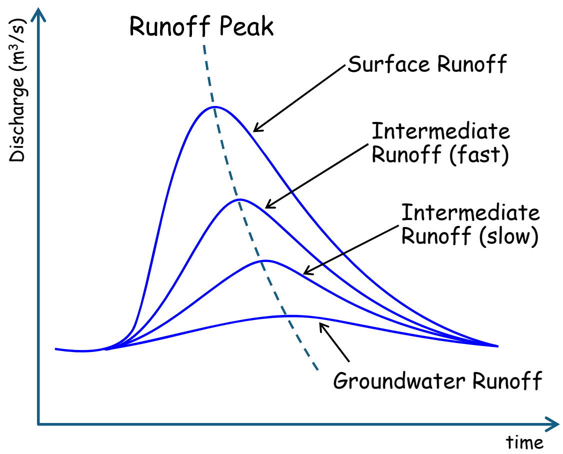


Fig- Runoff Peak (intellection)

A. Outline of RRI Model

Liner/Non Liner Model

If relation between observed rainfall and actual discharge is almost proportional, liner model shall be employed. Generally, Liner model would be employed in small basin. In Japan, liner model is used often for small river basin less than 50km^2.

On the other hand, if relation is not proportional, non-liner model shall be employed for runoff analysis, because large river basin has complicated runoff mechanism.

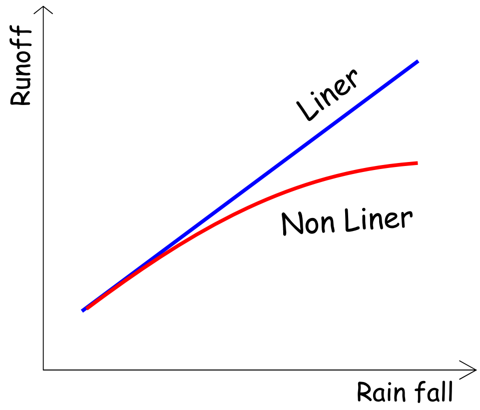


Fig- Notion of Liner/Non-Liner

Liner Model
- Rational formula
- Unit projection

etc.

Non - Liner Model
- Tank model
- Storage function method
- Characteristic curve method

etc.

A. Outline of RRI Model

Lumped/Distributed Hydrological Model

Runoff model shall be categorized to lumped model and distributed model.

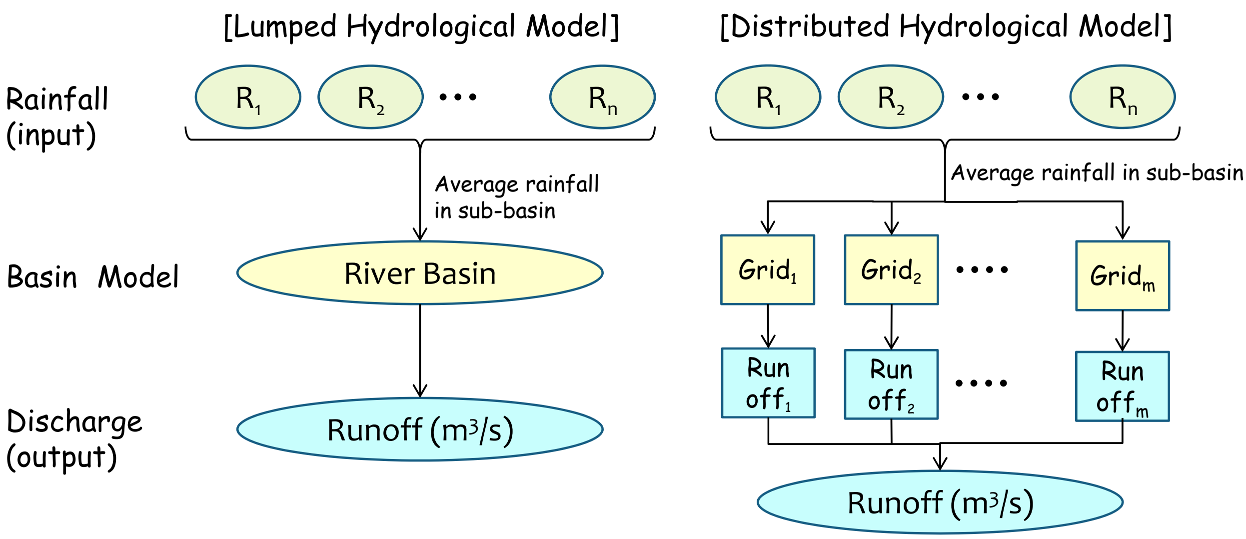


Fig- Schematic Diagram of Lumped/Distributed model

It could be said that distributed hydrological model is able to reflect the basin characteristic and describe detailed runoff characteristic.

A. Outline of RRI Model

Distributed hydrological model describes land form with digital elevation model (DEM) and counts the detailed land cover and geological condition. This kind of models estimate water movement with tank model and kinematic wave model etc.

For example, IFAS which is one of distributed hydrological model released by ICHARM calculates two runoff routes, surface flow and underground flow with tank model (see right figure).

Recently, distributed hydrological model has come into use for runoff analysis, because detailed elevation and land use products are easily obtained via internet for free.

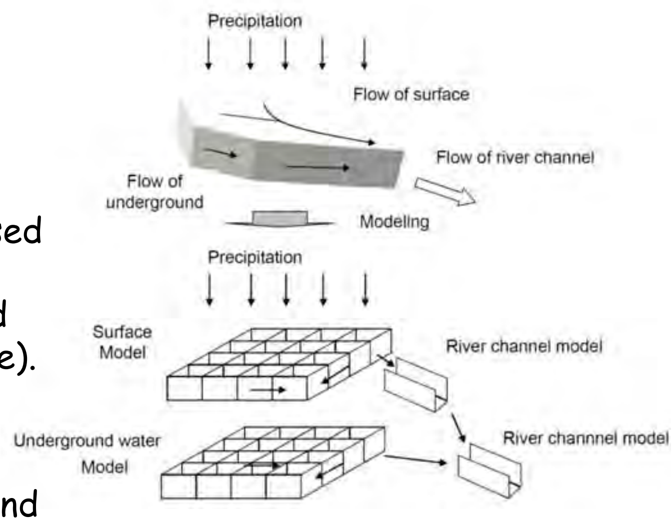


Fig- Schematic Image of IFAS

A. Outline of RRI Model

Selection of runoff model for hydrological analysis depends on…

- topographic features
- geographic features
- runoff characteristic
- size of river basin
- time of flood concentration (flood arrival time)
- land use condition etc.

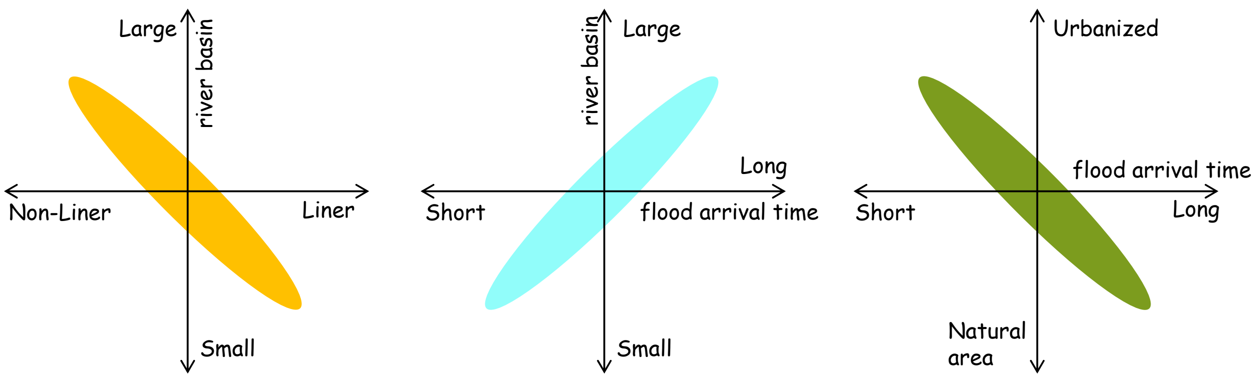


Fig- Notions of Runoff Characteristics

Runoff model employed for Mekong River basin and for Tokyo metropolitan area must be different!

A. Outline of RRI Model

For example…

Case1

Land use: urbanized

Basin area: less than 30km^2

Flood arrival time: very short (within 1hour)

Selected Model: "rational formula" , "unit projection "

Reason: uniform land use,
relation of rainfall and runoff is proportional (liner)

Case2

Land use: hills, paddy field and urbanized

Basin area: more than 10,000km^2

Flood arrival time: 3 days

Selected Model: "storage function model", "distributed model (RRI, IFAS)" etc.

Reason: need of consideration of difference of land use,
relation of rainfall and runoff is non liner

If it is difficult to decide which hydrological model should be used, runoff analysis would be conducted with number of models (methods) and a model with good-repeatability of observed discharge should be employed.

A. Outline of RRI Model

2) What is Inundation Analysis?

To estimate inundated area/depth with hydrological/hydraulic model

[Overflow from river]
Water level rises and river water overflows/spills into protected area.

[Inland flooding]
If local rainfall is not drained to rivers/canals, inland flooding could occur.

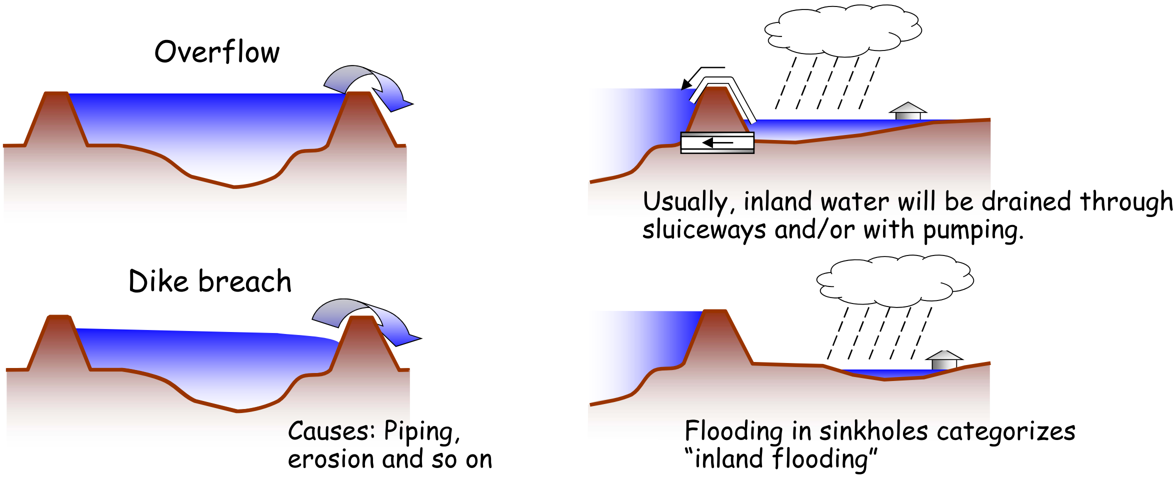
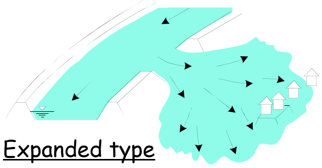
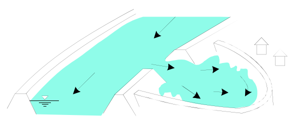
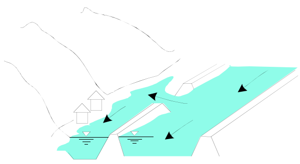


Fig- Typical Inundation Phenomenon

A. Outline of RRI Model

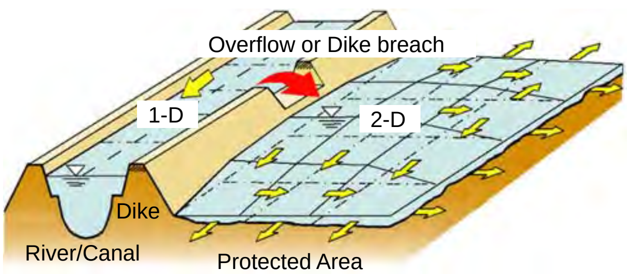
Movement of inundated water is formed according to topographic condition.

Table- Typical Inundation Forms (overflow flooding)

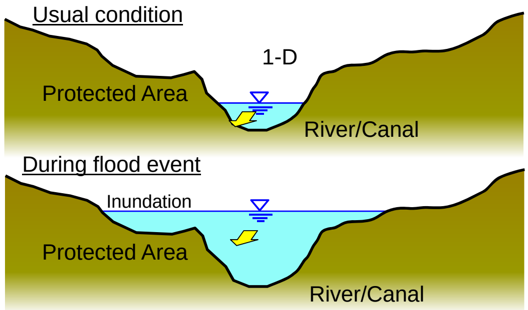
Inundation Type	Description
 Expanded type	[Topographic features] ❑ Land slope is low/flat ❑ Low land area lays expansively [Inundation forms] ❑ Inundated water expands in every direction (two dimensional) ❑ Inundated area is spread widely
 Storage type	[Topographic features] ❑ Land slope is low ❑ Inundated area is regulated by dike, embankment of railways/roads etc. [Inundation forms] ❑ Inundated water expands in every direction (two dimensional) ❑ Inundated area is limited, and water depth becomes deeper and also inundated term is long.
 Flow down type	[Topographic features] ❑ Land slope is steep ❑ Low land area is narrow and limited. [Inundation forms] ❑ Inundated water flows down along the river (one dimensional). ❑ Inundated area is narrow and inundated depth is shallow, however velocity of inundated water becomes fast.

A. Outline of RRI Model

A variety of inundation analysis model exists. Proper inundation model should be selected and employed for inundation analysis according to topographic features and inundation type in target area.



[Two dimensional flood analysis model]
This model is used in low land area where inundated water expands widely. In protected area, two dimensional unsteady method is employed. Also, one dimensional river analysis for estimation of water level in river shall be conducted and overflow water shall be calculated. Estimated overflow water is given to two dimensional model as boundary condition.



[One dimensional flood analysis model]
This model is used in case that inundation area is narrow along the river and inundation depth is dominated river water level (mainly employed in mountainous river).

Fig- Typical Inundation Analysis Model

A. Outline of RRI Model

3) Issues on Runoff/Inundation Analysis

As mentioned above, river discharge consists of several runoff, including surface runoff, intermediate runoff and groundwater runoff etc. Generally, Japanese land is almost mountain topography and land slope is steep, therefore flood water mainly consists of surface runoff and fast intermediate runoff. Also flood arrival time is short, which implies that evaporation, infiltration and ground water runoff do not contribute to flood scale so much.

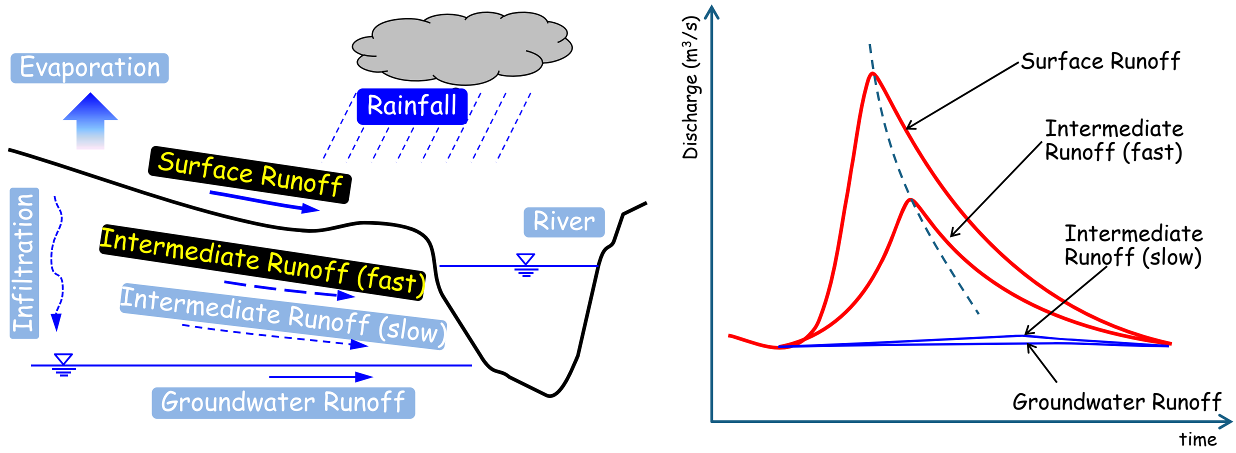


Fig- Runoff Mechanism (Japanese River)

A. Outline of RRI Model

On the other hand, for example, in large scale river like the Chao Phraya River and the Mekong River, not only surface/fast-intermediate flow but also slow-intermediate flow, in some cases, groundwater flow, could contribute to flood scale. And, evaporation and infiltration should be counted due to long flood duration. In addition, natural inundation and retarding in low land area contribute to decrease of river flow.

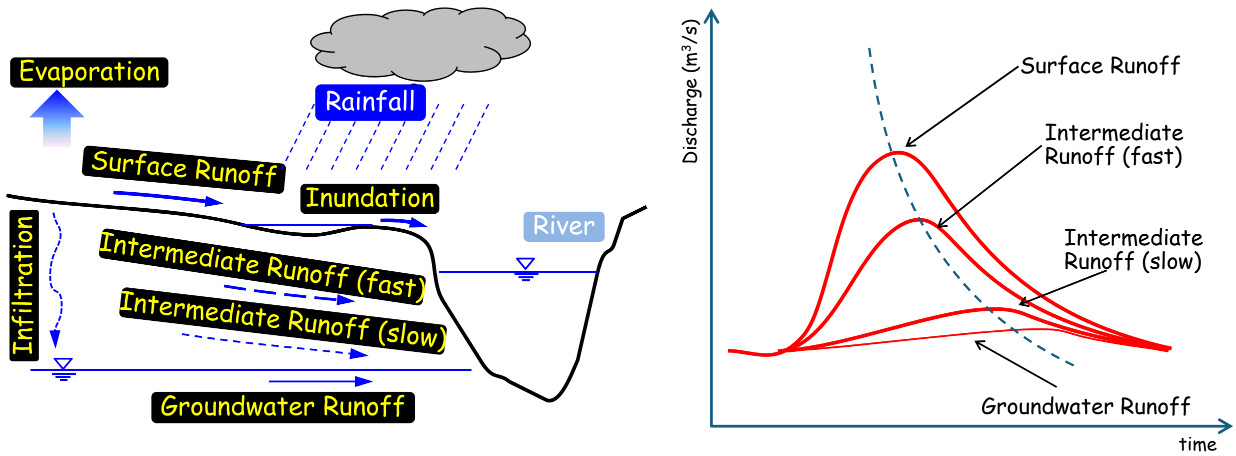


Fig- Runoff Mechanism (Large Scale River)

A. Outline of RRI Model

In some ways, runoff analysis in Japanese river is not difficult because hydrological factors contributing flood scale is limited to surface and intermediate-runoff. However, in large scale river, many hydrological factors must be considered.

In order to calculate/estimate river discharge adequately in large river basin, the following hydrological phenomenon should be counted in runoff analysis model,

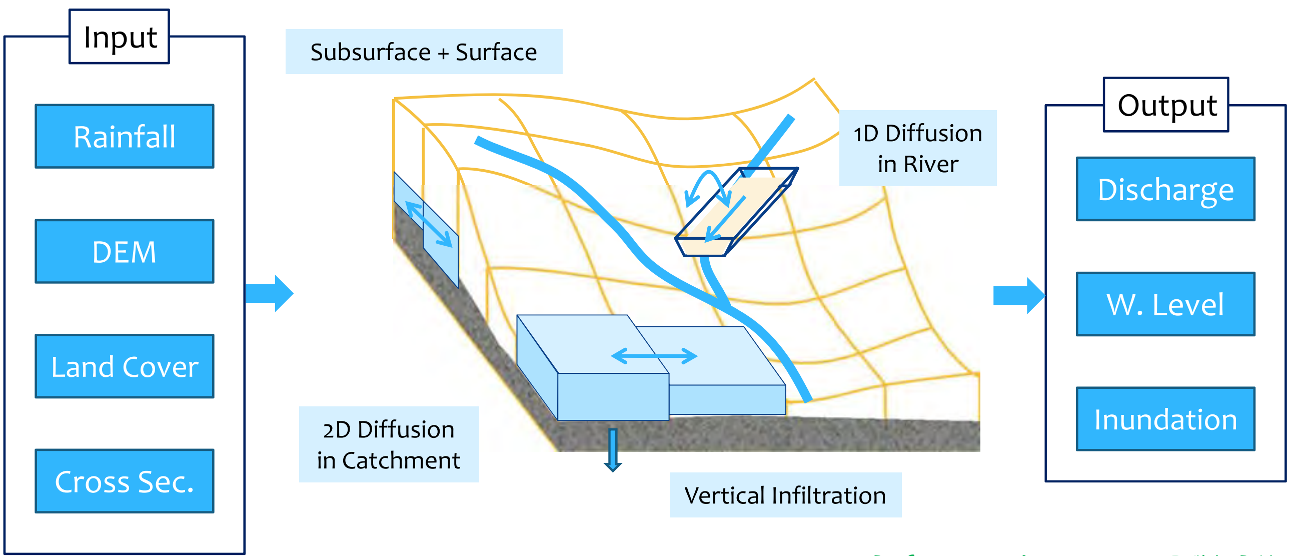
- ☐ All runoff
  (surface flow, fast/slow intermediate flow and groundwater flow)
- ☐ Evaporation
- ☐ Infiltration
- ☐ Inundation (retarding function in lowland)

Especially, storage function caused by inundation impacts on river discharge, but commonly-used runoff model seems not to consider an influence of inundation. Usually, runoff analysis and inundation analysis are conducted separately and output from runoff analysis (hydrograph) is given to inundation model as boundary condition.

A. Outline of RRI Model

A-4) Advantages of RRI Model

RRI Model calculates runoff and inundation phenomenon at the same time considering evaporation/infiltration. In addition, this model can do a flood routing analysis (river flow).

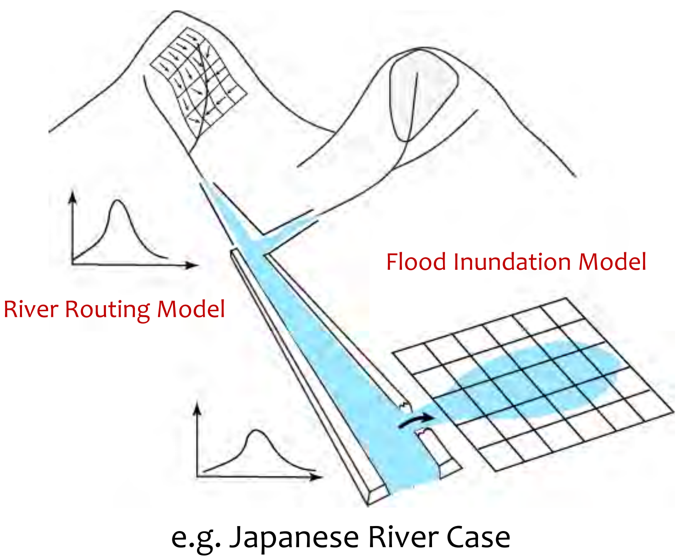


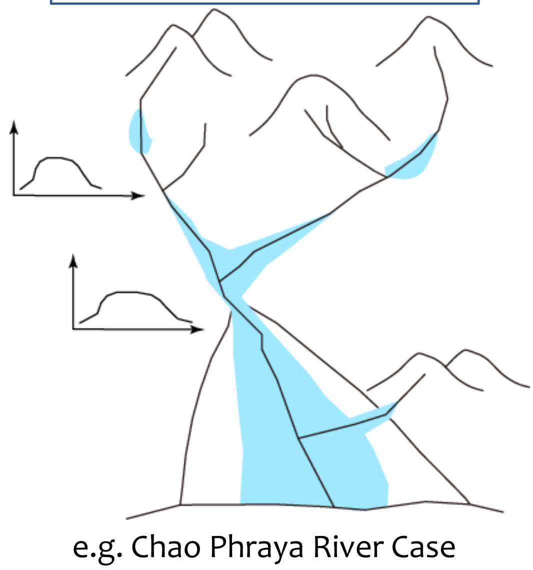
Reference: Dr. Sayama, ICHARM

Fig- Structure of RRI Model

A. Outline of RRI Model

In Chao Phraya River, influence of storage function caused by inundation is large, therefore runoff analysis considering inundation and river routing is better for understanding actual hydrological condition.





Reference: Dr. Sayama, ICHARM

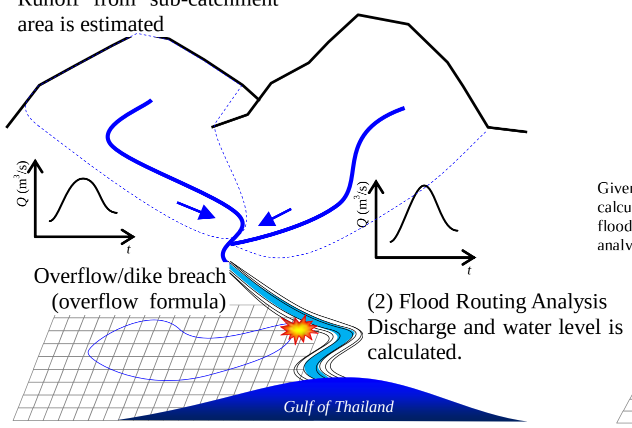
Fig- Structure of Runoff/Inundation Model

A. Outline of RRI Model

RRI Model is able to estimate runoff from the river basin considering inundation since local rainfall is given to two-dimensional calculation girds directly, which means that RRI Model can calculate inland-flooding.

Three hydrological models is integrated
Hydrological values calculated with each model become boundary condition

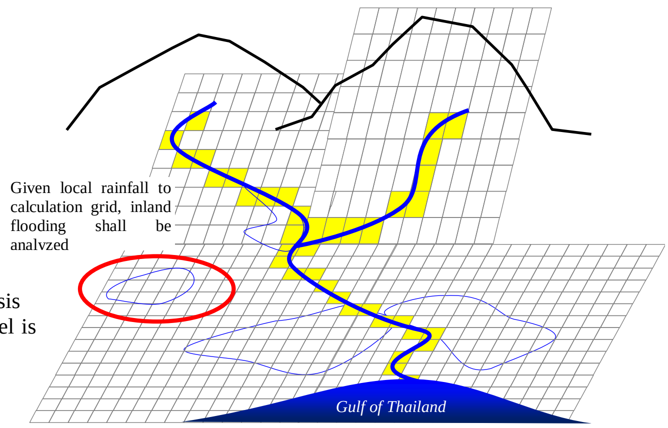
(1) Runoff Analysis
Runoff from sub-catchment area is estimated



(3) Inundation Analysis
Inundated area and depth is estimated.

【MIKE Series】

River basin built with elevation grid
Local rainfall is given to each calculation grid and runoff calculation is conducted. Flood inundation is described as a part of surface runoff. Regarding flood routing analysis, cross-sectional property is given to calculation grid for river channel (painted yellow).



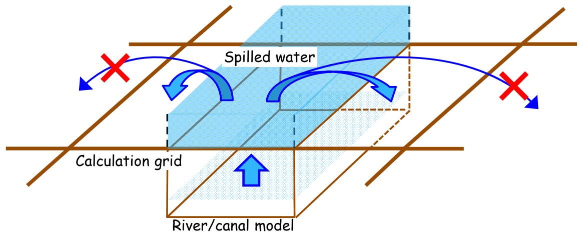
【RRI Model】

A. Outline of RRI Model

A-5) Future Outlook

1) Modification of flood routing model:
Hydraulic calculation for diversion and river-crossing structures should be equipped in the model. At the present, user have to configure the diversion ratio separately at diversion point.

2) Estimation of overflow:
Due to the fundamental structure of RRI Model (see right figure), just one overflow volume shall be estimated because left and right individual dike height is not considered. It is preferable to configure right-and-left dikes and estimate each overflow volume.



River/canal is built in each calculation grid. One representative dike height is set-up in RRI Model. If river water level exceeds the ground level (elevation of DEM), spilled water volume flows into the calculation grid with river/canal, NOT circumjacent calculation grids.

3) Result Viewer
As of August 2013, RRI simulator with result viewer (Graphical User Interface, GUI) has been developed by FRICS.

A. Outline of RRI Model

A-6) Others

1) About IFAS released by ICHARM

The difference between RRI Model and IFAS are shown in following table.

Items	RRI Model	IFAS
Model Type	Distributed hydrological model	Distributed hydrological model
Runoff model	Diffusion wave or Kinematic wave model (selectable)	Tank model (two tanks, for surface and ground water runoff)
Ground water	Green Ampt model and/or Darcy's rule model (selectable)	ditto
Flood routing model	1-dimensional unsteady flow model Diffusion wave model (considering actual cross-section)	Tank model (one tank)
Inundation model	2-dimensional unsteady flow model :Diffusion wave model	N/A
Distributer	ICHARM (delivery method is under consideration as of Sep 2013)	ICHARM (get from internet for free! http://www.icharm.pwri.go.jp/research/ifas/)

A. Outline of RRI Model

2) Differences of RRI Model FRICS Version

RRI Model employed for the flood forecasting system by FRICS is version 1.3. On the other hand, RRI Model used for this study is version 1.4β. Basically, calculation processes of both version is completely same.

In version 1.4β, user is able to input cross-sectional property and consider an influence of river cross-section shape on flow condition. Version 1.4β is deemed to calculate water level more properly than version 1.3. but version 1.4β requires much calculation time (approx. need more than twice time, in Chao Phraya River case). From the point of view of practical utility such as early warning system, it could be said that version 1.3 is superior to version 1.4β.

B. Introduction of the result of M/P study with RRI Model

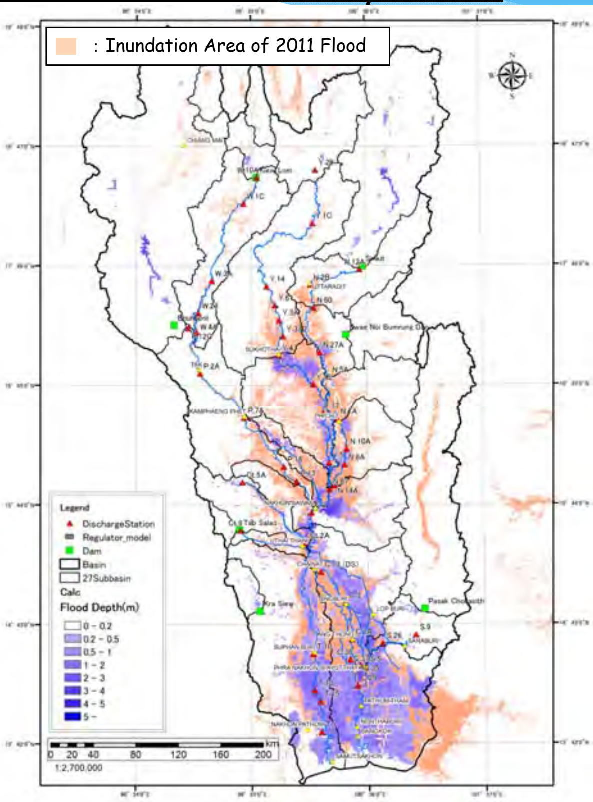
To examine the usability of RRI Model, flood analysis on equal terms with M/P study shall be done with RRI Model (version 1.4β). The calculation cases are shown in following table.

Table- Simulation Cases with RRI Model

Case	Countermeasures by Thai side (ongoing)		Proposed Countermeasures						
			C7	C2	C4	C5			C6
	Protection dike around the economic zone	Dike raising on Chao Phraya River and Pasak River (by BMA and DOH)	Improved existing dam operation	New dams	Improvement of the retention areas (monkey cheeks)	Dyke raising up to DHWL + freeboard of 0.5m (all river/canal)	East/west floodways [flow capacity]	Ayutthaya Bypass	Construction of central floodway [flow capacity]
Re-production 2011yr Flood	Considering dike breaches								
SCWRM's M/P	●	●	●	●	●	●	● [1,500m³/s]	●	● [500m³/s]
Combination-1 (proposed by JST)	●	●	●	-	-	-	-	●	● [500m³/s]
Combination-2 (proposed by JST)	●	●	●	-	-	-	-	●	● [1,000m³/s]

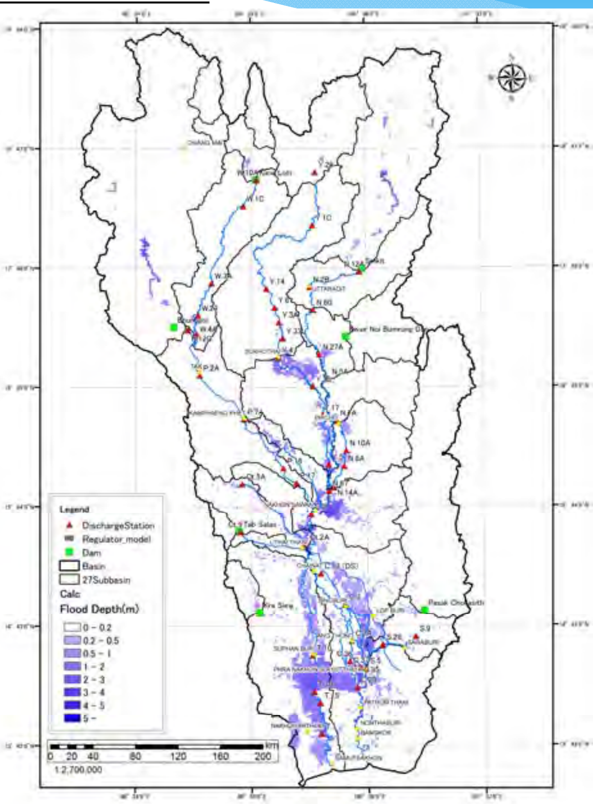
B. Introduction of the result of M/P study with RRI Model

B-1) Re-production Calculation of 2011yr Flood



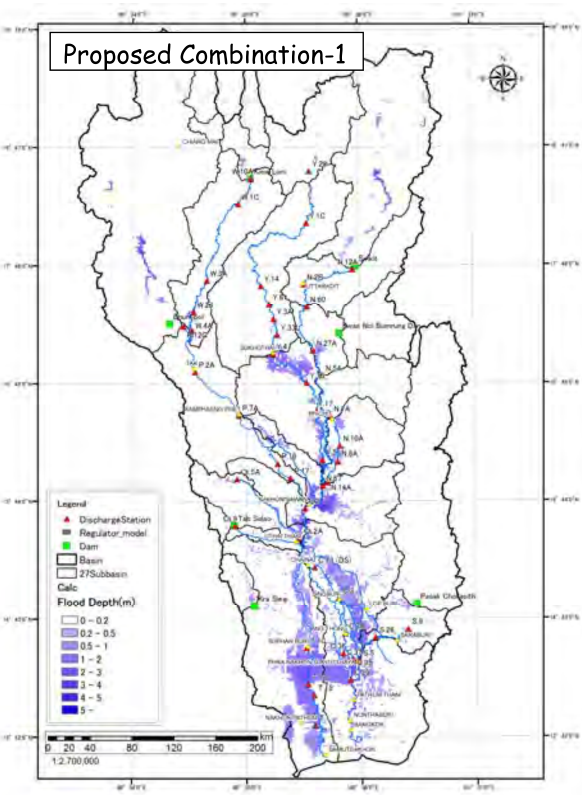
B. Introduction of the result of M/P study with RRI Model

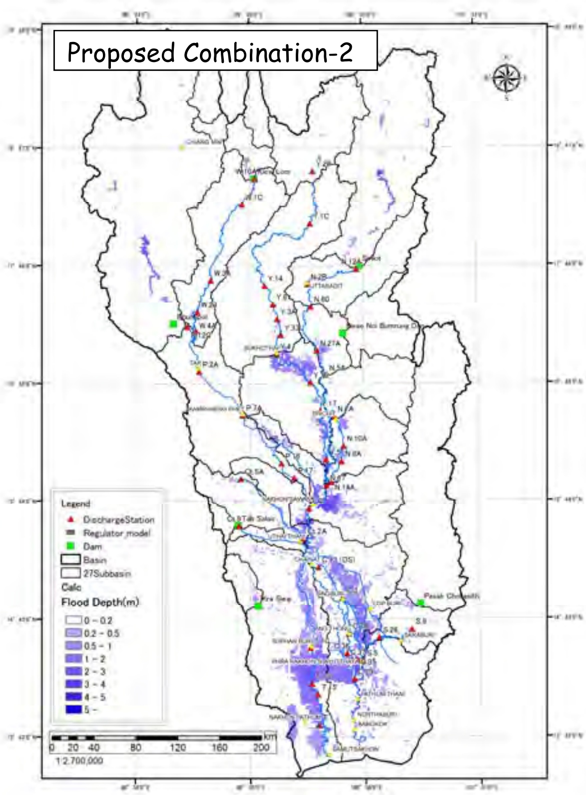
B-2) Result of SCWRM's M/P



B. Introduction of the result of M/P study with RRI Model

B-3) Result of Combination-1 and 2 Proposed by Jica Study Team





B. Introduction of the result of M/P study with RRI Model

B-4) Findings and Recommendations

- ✓ Inundation area/depth in 2011 flood almost agrees with the observed data.
- ✓ Even though the adjustable parameter is a few (roughness coefficient of both rivers/canals and flood plain, and hydraulic conductivity of soils), reproducibility of past flood is relatively high, which says that RRI Model has a high practical utility and beneficial effect on flood control plan and warning system in developing countries.
- ✓ It could be said that effectiveness of proposed flood countermeasures can be evaluated to some extent with RRI Model.
- ✓ Reliability of re-production of inundation appearance around major river-crossing structure (ex, Chaophraya dam) is not so high because RRI Model does not calculate overflow volume with weir formula (ex, Honma formula). For improvement of accuracy of inundation area around river crossing structures such as weirs, water gates etc. it is desirable to calculate water movement around them with hydraulic formulas.
- ✓ Also, diversion of rivers/canals are not calculated with equation of continuity and motion equation. Diverted water should be estimated with hydraulic mathematical formulas too.

C. Practice of RRI Model

Let's try to build RRI Model and conduct hydrological analysis!

In this seminar, you will build a RRI Model for sample river basin and conduct hydrological analysis by yourself.
It is sure that this experiences will help with establishments of flood control plan, integrated water resource management plan and so on.

C. Practice of RRI Model

Contents of RRI practice

1. Understand the Necessary Data
C-1) Necessary Data for RRI Model P34
C-2) Sample Data for RRI Model P35

2. Prepare Input Data
C-3) Preparing Input Topography Data P40
C-4) Preparing Input Rainfall Data P60

3. Execute RRI
C-5) Execute RRI P61

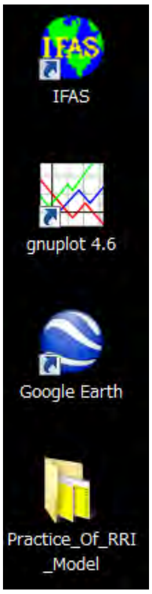
5. Try Simulation with Additional Conditions
C-7) Try Simulation with additional conditions P86
- ✓ Change downstream boundary conditions P86
- ✓ Change upstream boundary conditions P88

4. View the Results
C-6) View the Results P63
- ✓ Draw hydrographs with EXCEL P64
- ✓ Visualize inundation Depth with GNUPLOT P71
- ✓ Displaying results on Google Earth P77

C. Practice of RRI Model

C-0) Advance Preparation

Before building the RRI Model, please download as following software (for free) and confirm the installation of them on your PC.



IFAS: To use when users prepare topographic data.
http://www.icharm.pwri.go.jp/research/ifas/

GNUPLOT: To use when users check/view the result.
http://www.gnuplot.info/

Google Earth: To use when users check/view the result.
http://www.google.com/earth/download/ge/agree.html

"Practice_of_RRI_Model" Folder: input datasets, output datasets , execution engine of RRI Model are stored, **provided by JST**.

C. Practice of RRI Model

In this seminar, IFAS is used for preparation of geographical dataset.

RRI User Manual released by ICHARM instructs that topographical data is to be prepared with ArcGIS (©esri). However, ArcGIS is not available for free.

The main function of IFAS system is shown in the right figure. IFAS does not have a function as geographical editor, but it can make same kind of geographical data for RRI Model.

In particular, three 2-dimensional data such as
1) elevation data,
2) flow direction
3) flow accumulation data
shall be prepared with IFAS.

Getting Rainfall Data
【 Satellite-based rainfall data 】
･3B42RT
･GSMap
:

Modeling
【 building channel network : DEM data 】
･GTOPO30
･Hydro1k
:
IFAS makes geographical data in the process of modeling.
【 Estimation of parameter 】
･land-use
･soil
:

Runoff analysis

Display of results

Fig- Main Functions of IFAS (Integrated Flood Analysis System)

C. Practice of RRI Model

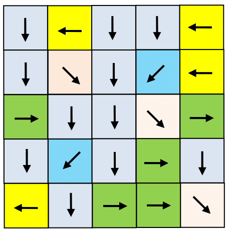
C-1) Necessary Data for RRI Model

Topological Data

(1) Elevation data
(2) Flow direction data
(3) Flow accumulation data

In the RRI Model, three data with ASCII data format must be prepared.

Essential data!



Flow direction

1	0	0	1	0
2	0	1	3	0
3	4	7	0	0
0	5	8	0	2
7	0	9	10	14

Flow accumulation

(4) Rainfall Data

Rainfall data must be prepared.

Essential data!

Other Data (optional as necessary)

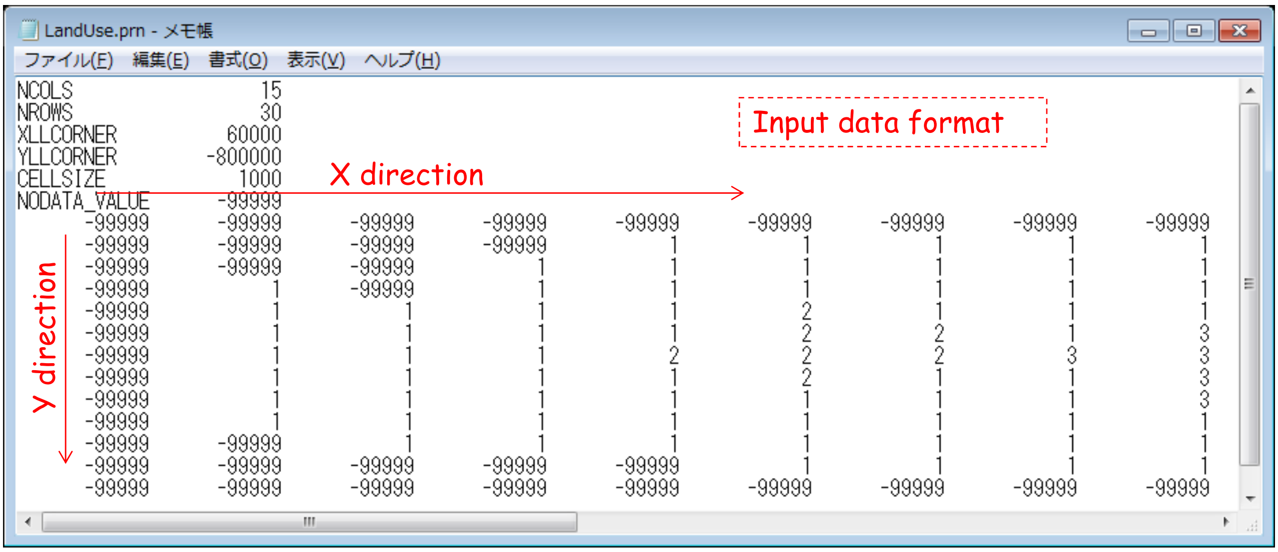
(5) Land Use data
(6) River Section data
(7) Boundary data (upstream: inflow, downstream: tidal data)
etc.

C. Practice of RRI Model

C-2) Sample Data for RRI Model

(1) Elevation data (DEM)
(2) Flow direction data (DIR)
(3) Flow accumulation data (ACC)

Same as GIS data format (*.asc)



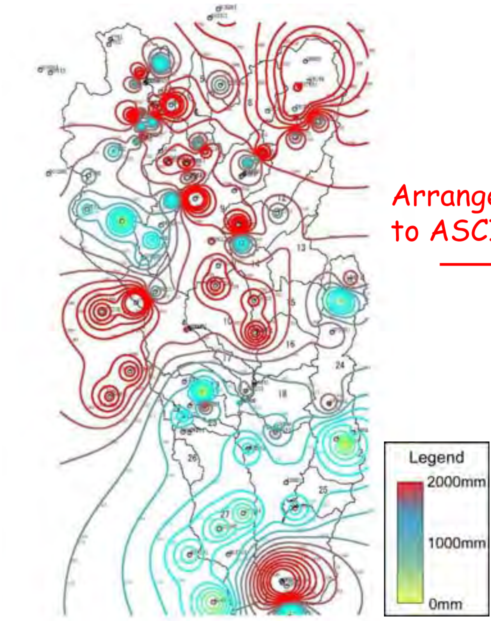

```
NCOLS              15
NROWS              30
XLLCORNER       60000
YLLCORNER     -800000
CELLSIZE         1000
NODATA_VALUE   -99999
-99999 -99999 -99999 -99999 -99999 -99999 -99999 -99999 -99999
-99999 -99999 -99999 -99999      1      1      1      1      1
-99999 -99999 -99999      1      1      1      1      1      1
-99999      1 -99999      1      1      1      1      1      1
-99999      1      1      1      1      2      1      1      1
-99999      1      1      1      1      2      2      1      3
-99999      1      1      1      2      2      2      3      3
-99999      1      1      1      1      2      1      1      3
-99999      1      1      1      1      1      1      1      3
-99999      1      1      1      1      1      1      1      1
-99999 -99999      1      1      1      1      1      1      1
-99999 -99999 -99999 -99999 -99999      1      1      1      1
-99999 -99999 -99999 -99999 -99999 -99999 -99999 -99999 -99999
```

C. Practice of RRI Model

C-2) Sample Data for RRI Model

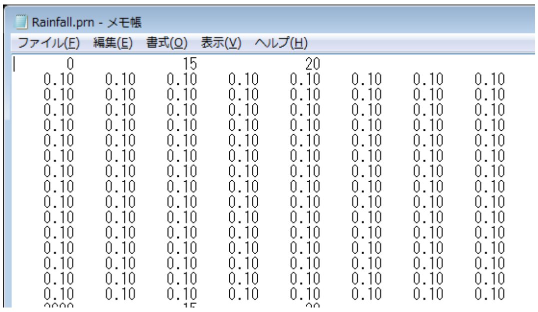
(4) Rainfall data

Collected rainfall data has to be converted to two-dimensional data format (*.asc).



Rainfall distribution (sample)

Arrange rainfall data to ASCII data format →

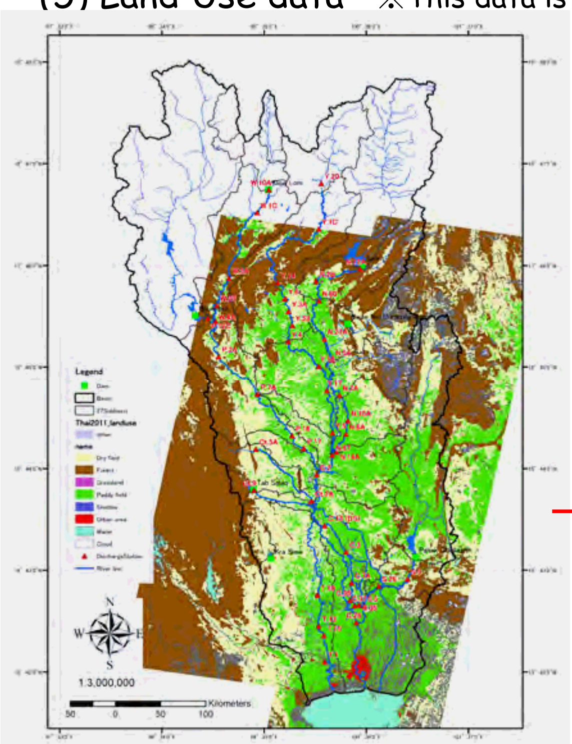


```
Rainfall.prn - メモ帳
ファイル(F) 編集(E) 書式(O) 表示(V) ヘルプ(H)
        0              15              20
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
     0.10     0.10     0.10     0.10     0.10     0.10     0.10     0.10
```


C. Practice of RRI Model

C-2) Sample Data for RRI Model

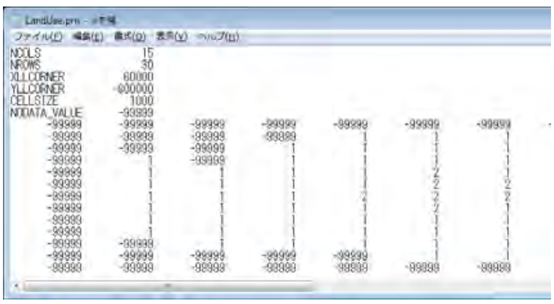
(5) Land Use data ※This data is a optional



Land use condition (sample)

In order to set up several parameters according to land use condition including roughness coefficient of protected land and vertical infiltration etc., identification code can be given to each calculation grids.

→



```
LandUse.prn - メモ帳
ファイル(F) 編集(E) 書式(O) 表示(V) ヘルプ(H)
NCOLS             15
NROWS             30
XLLCORNER      60000
YLLCORNER    -900000
CELLSIZE        1000
NODATA_VALUE  -99999
   -99999     -99999     -99999     -99999     -99999     -99999     -99999
   -99999     -99999     -99999     -99999          1          1          1
   -99999     -99999     -99999          1          1          1          1
   -99999          1     -99999          1          1          1          1
   -99999          1          1          1          1          2          1
   -99999          1          1          1          1          2          2
   -99999          1          1          1          2          2          2
   -99999          1          1          1          1          2          1
   -99999          1          1          1          1          1          1
   -99999          1          1          1          1          1          1
   -99999     -99999          1          1          1          1          1
   -99999     -99999     -99999     -99999     -99999          1          1
   -99999     -99999     -99999     -99999     -99999     -99999     -99999
```

C. Practice of RRI Model

C-2) Sample Data for RRI Model

(6) River/Canal data

Mainly three kinds of river data (river width, depth and height of dike) shall be given as following. Please refer to User Manual of RRI Model (version 1.3) for detailed explanation of those parameters

RRI_Input.txt

```
L33  20                           # riv_thresh
L34  5.0d0                        # width_param_c
L35  0.35d0                       # width_param_s
L36  0.95d0                       # depth_param_c
L37  0.20d0                       # depth_param_s
L38  0.d0                         # height_param
L39  20                           # height_limit_param
L40
L41  0
L42  ./infile/solo/width_solo.txt
L43  ./infile/solo/depth_solo.txt
L44  ./infile/solo/height_solo.txt
L45
```

■RRI_Input.txt is control file of RRI Model.

C. Practice of RRI Model

C-2) Sample Data for RRI Model

(7) Boundary data

Discharge data and/or water level data can be set on arbitrary grids as a boundary condition.

The example data set which gives a tidal data in the river mouth is shown in the right figure. The data includes location of grid given to the data, time-step and time-series water level.

REV_tide_level.txt
ファイル(F) 編集(E) ヘルプ(H)

Time-step (unit: second)

Water Level (E.L.m)

```
2
y(lat)   384
x(lon)   166
0        10.713
10800    11.803
21600    11.803
32400    10.813
43200    10.523
54000    11.373
64800    11.403
75600    10.513
86400    10.483
97200    11.673
108000   11.833
118800   10.773
129600   10.213
140400   11.293
151200   11.743
162000   10.823
172800   10.373
183600   11.513
194400   11.853
205200   10.773
216000   9.983
226800   11.093
237600   11.953
248400   11.173
259200   10.413
270000   11.353
280800   11.853
```

C. Practice of RRI Model

Let's try to do it for real !!

C-3) Preparing Input Topography Data

Let's make 3 essential data as listed below, by using IFAS and supplemental tools (developed by CTII).

(1) Elevation data
(2) Flow direction data
(3) Flow accumulation data

The target river is "Phetchaburi" river in the southwest from Bangkok.

C. Practice of RRI Model

C-3) Preparing Input Topography Data

Please confirm the following advance preparation is done

1) Install IFAS on your PC

2) Copy the data of GTOPO 30 to your PC

(elevation data, resolution is 30 seconds, approx. 900m)

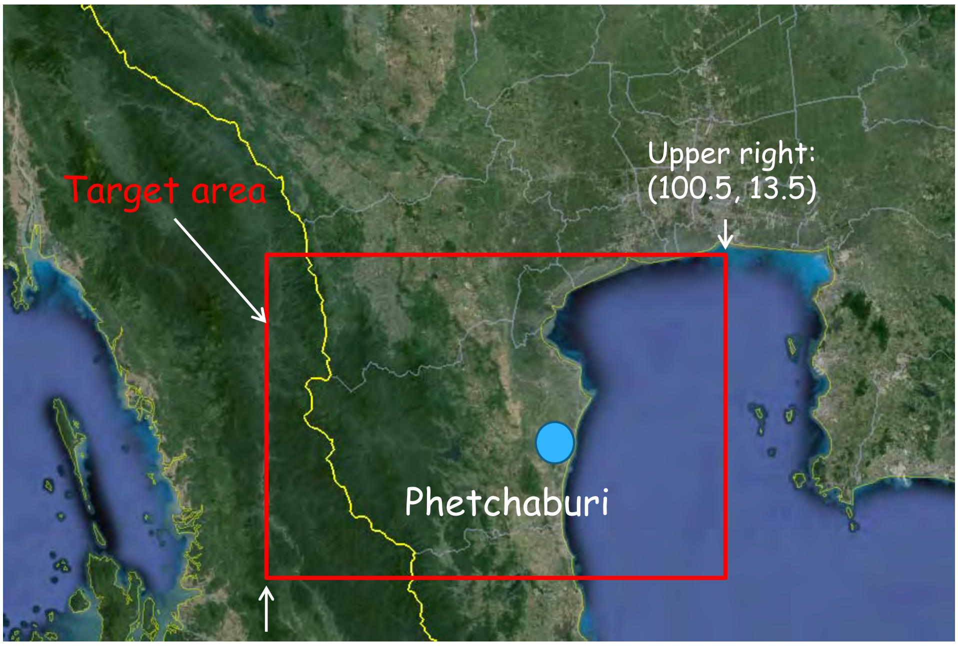
*User can get the data for free!

http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10003_1 (NASA)

C. Practice of RRI Model

C-3) Preparing Input Topography Data

Acquire the coordinates (the upper right and the lower left) of the target area with Google earth etc.



lower left:
(99.0, 12.5)

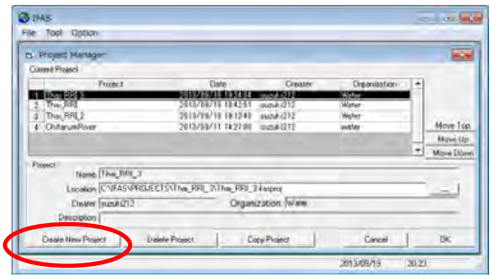
C. Practice of RRI Model

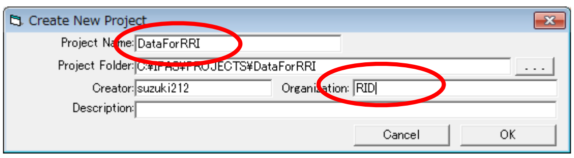
C-3) Preparing Input Topography Data

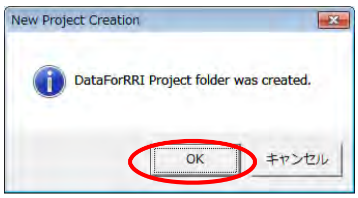
■ Set up IFAS and create an new project.

Double-click the icon on the desktop.

1. Set up IFAS
2. Create new project
3. Set 'project name' and 'organization'



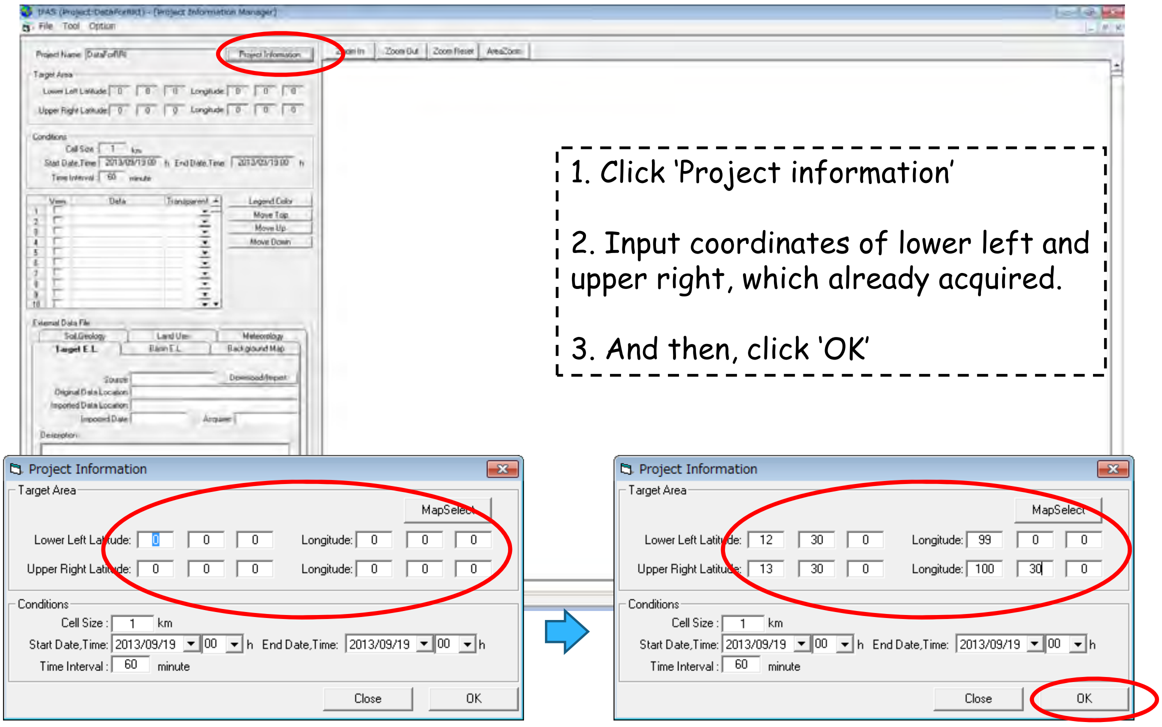




C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the coordinates.



1. Click 'Project information'

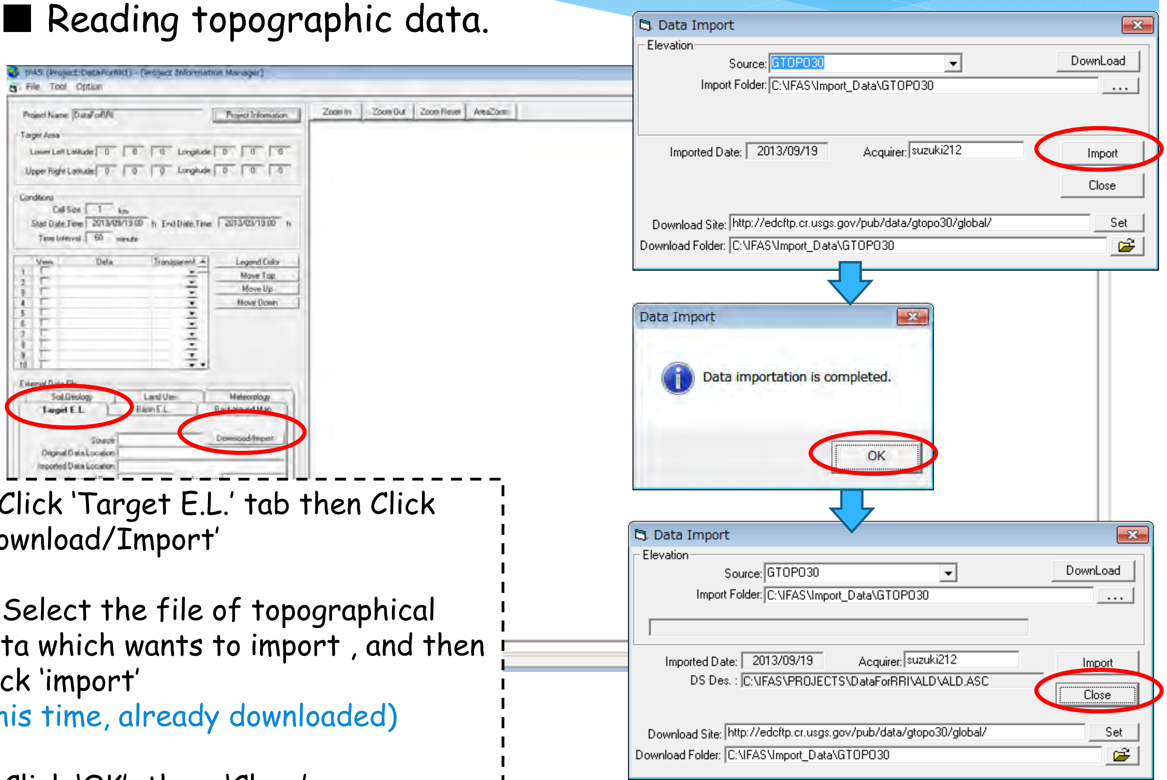
2. Input coordinates of lower left and upper right, which already acquired.

3. And then, click 'OK'

C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Reading topographic data.



1. Click 'Target E.L.' tab then Click 'Download/Import'

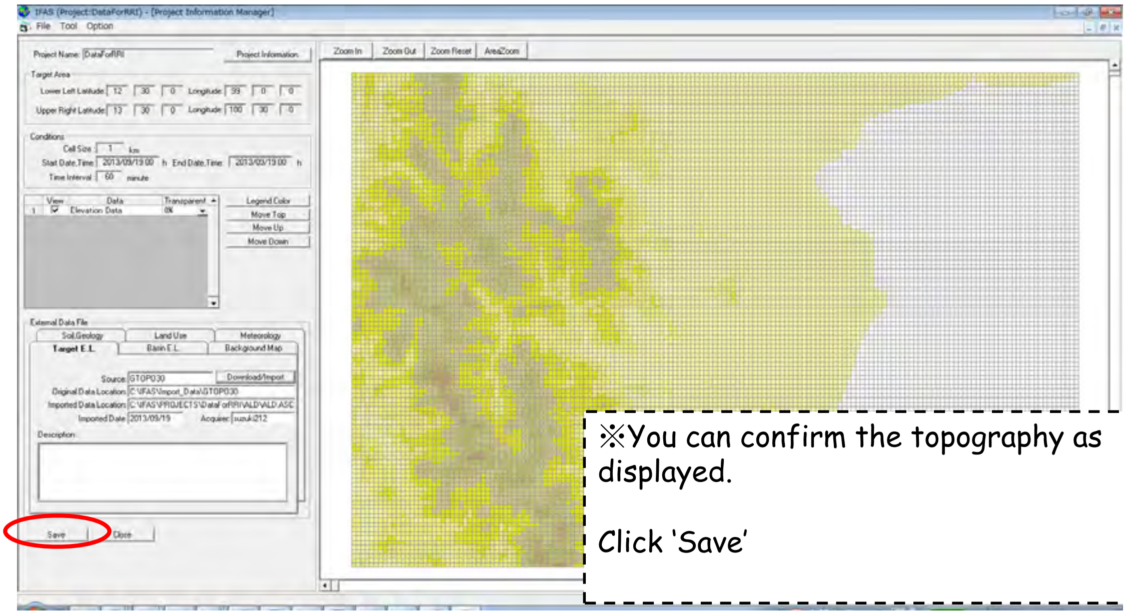
2. Select the file of topographical data which wants to import , and then click 'import'
(this time, already downloaded)

3. Click 'OK' then 'Close'

C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ To load topographic data from GTOP30.



※You can confirm the topography as displayed.

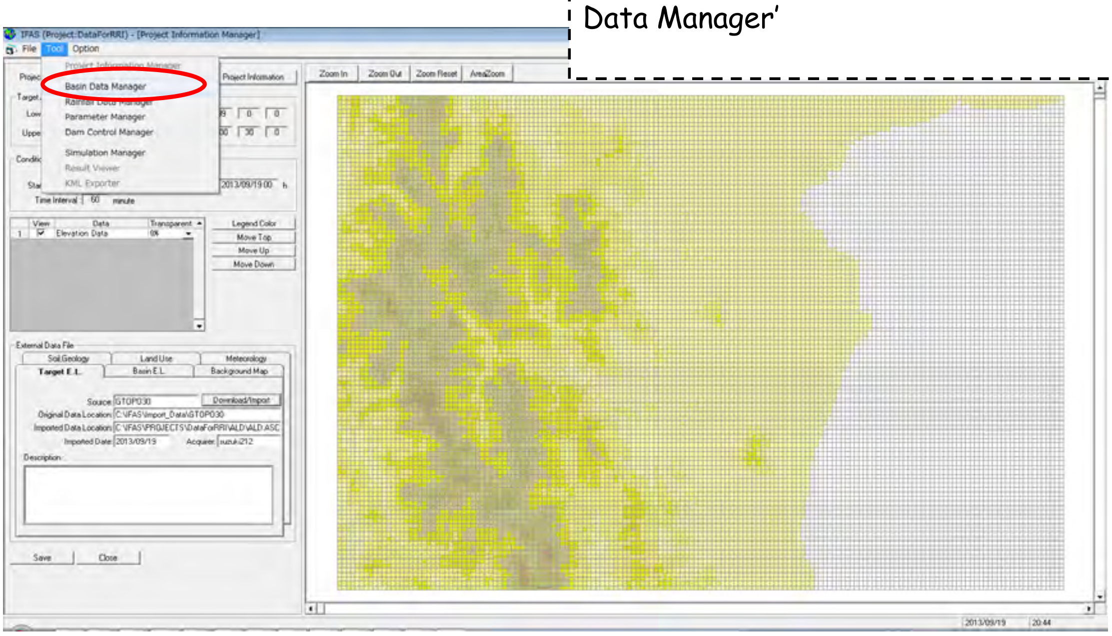
Click 'Save'

C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide-1

On the "Tool" toolbar, select 'Basin Data Manager'

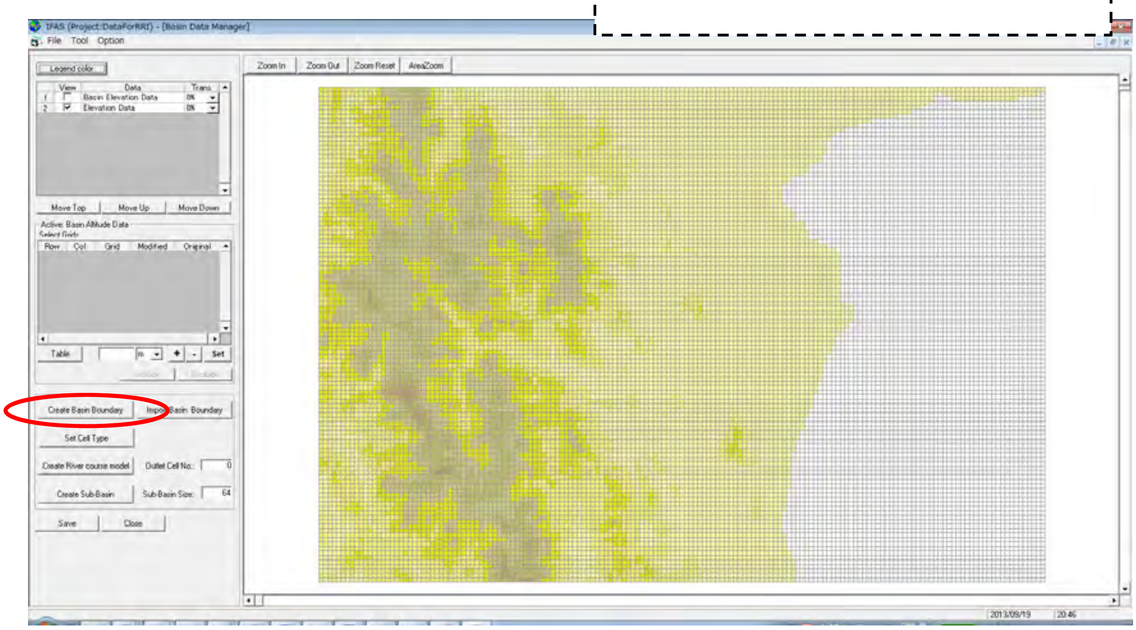


C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide -2

Click 'Create Basin Boundary'

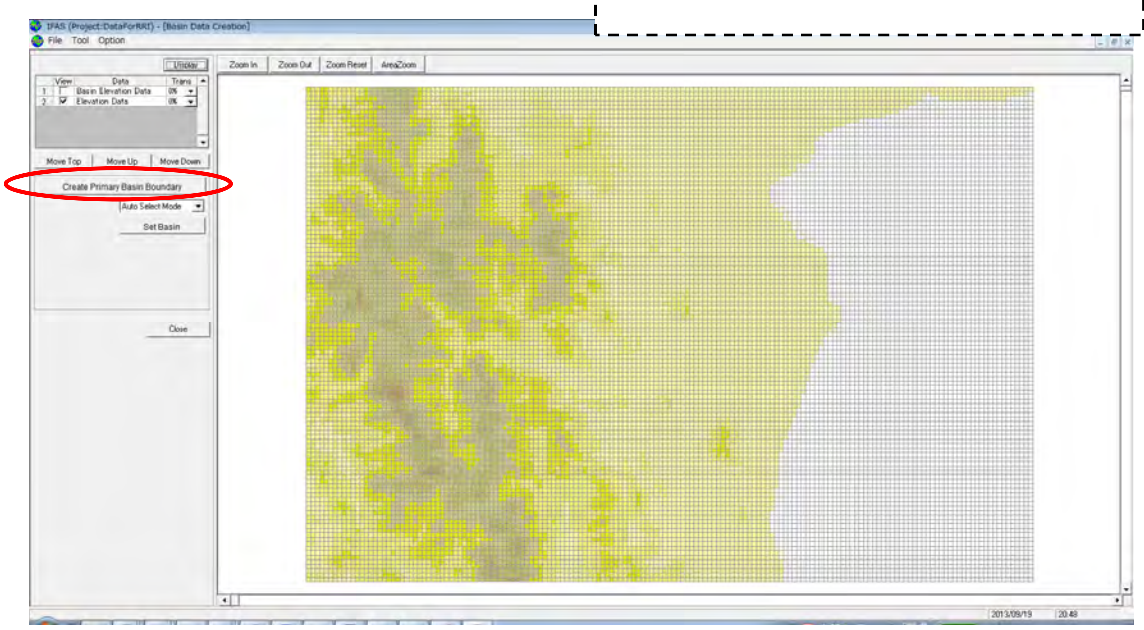


C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide -3

Click 'Create Primary Basin Boundary'

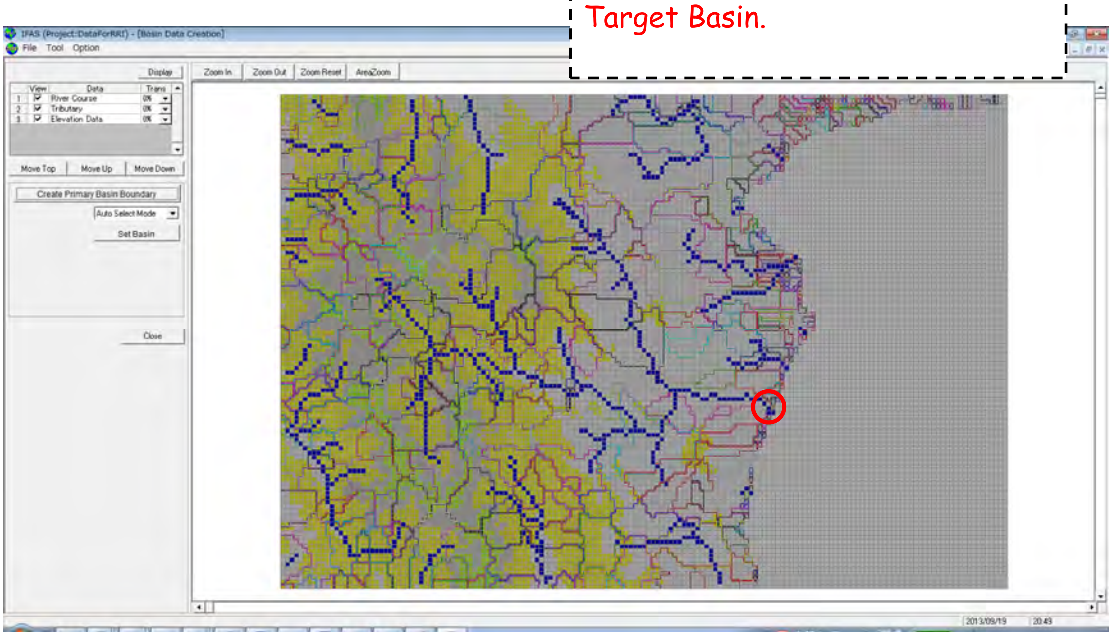


C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide -4

Click the River mouth mesh of Target Basin.

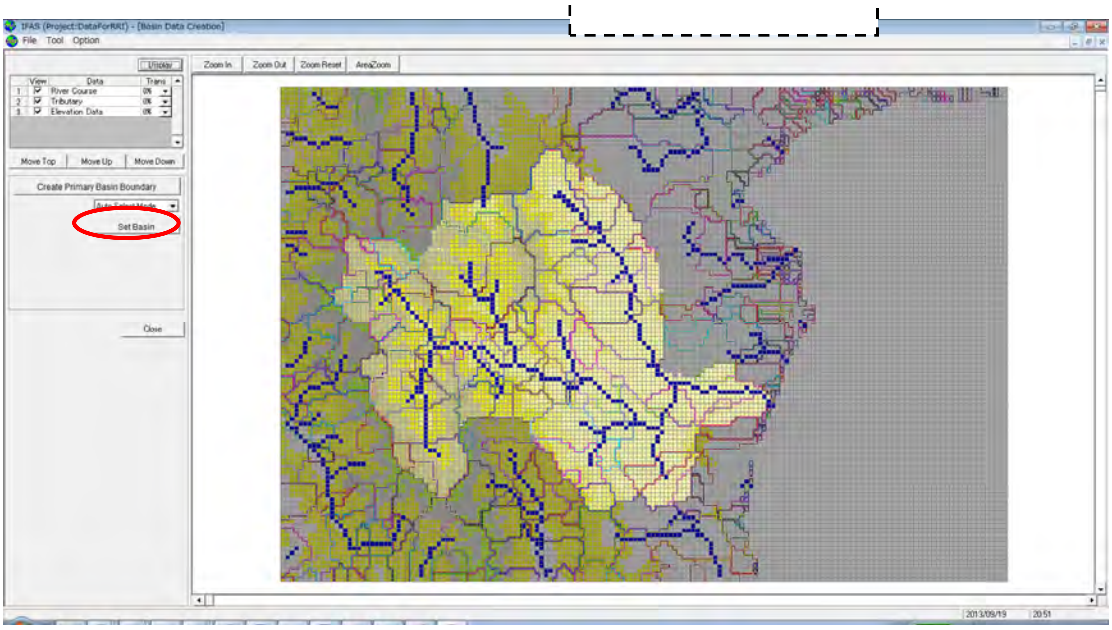


C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide -5

Click "Set Basin".

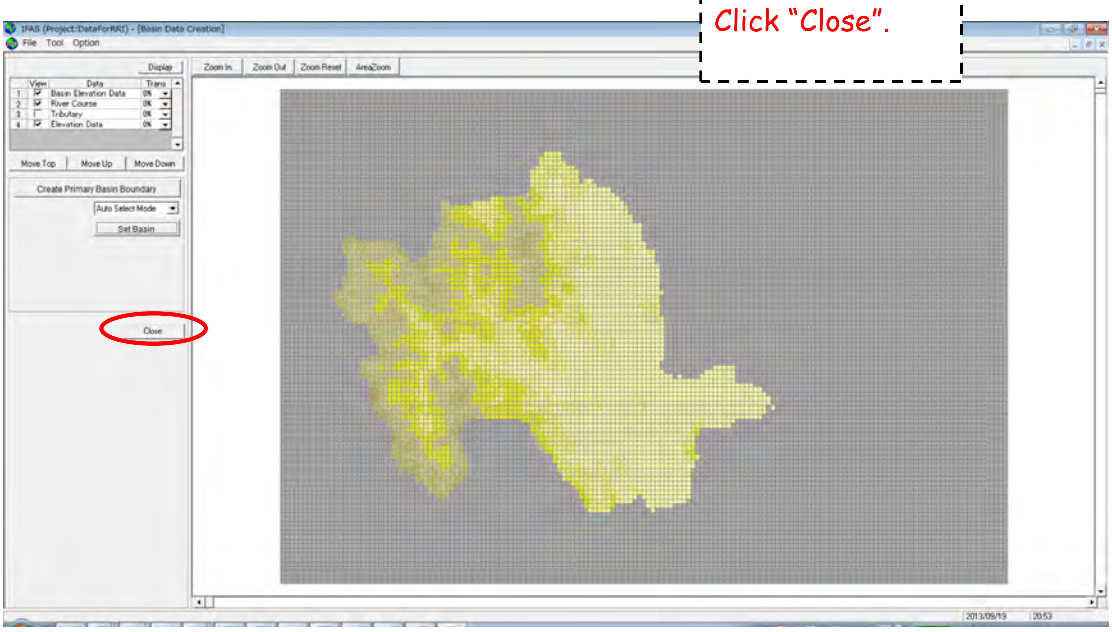


C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide -6

Click “Close”.



C. Practice of RRI Model

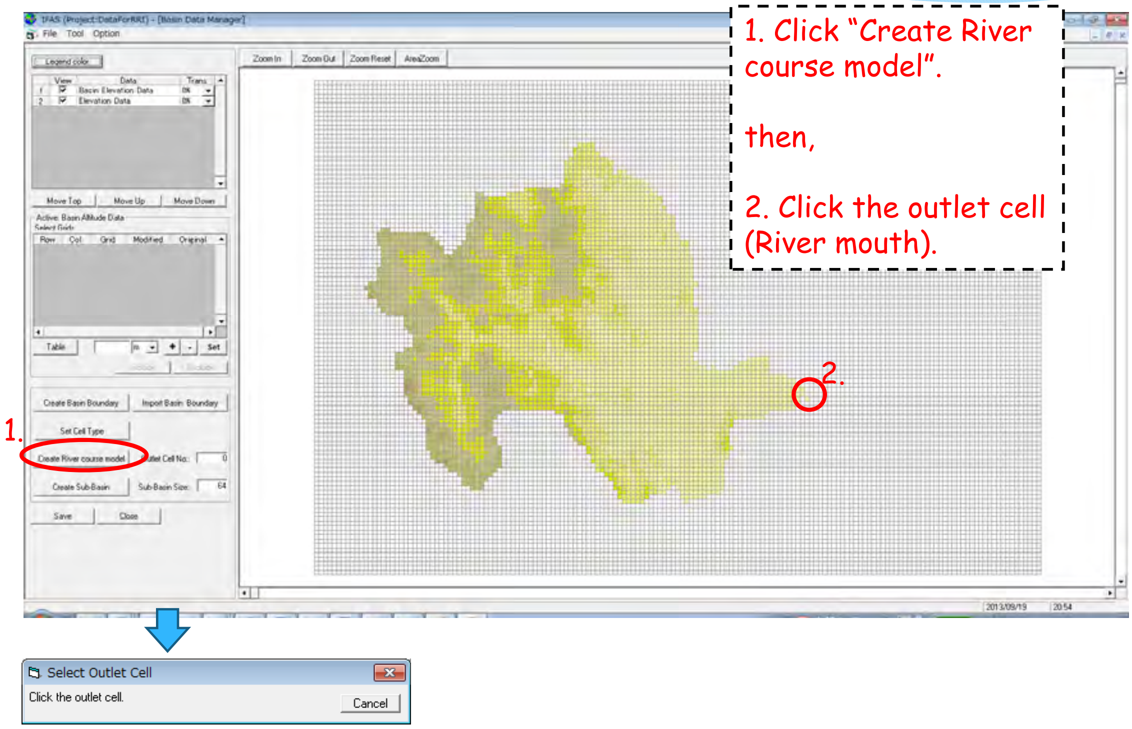
C-3) Preparing Input Topography Data

■ Set the basin divide -7

1. Click “Create River course model”.

then,

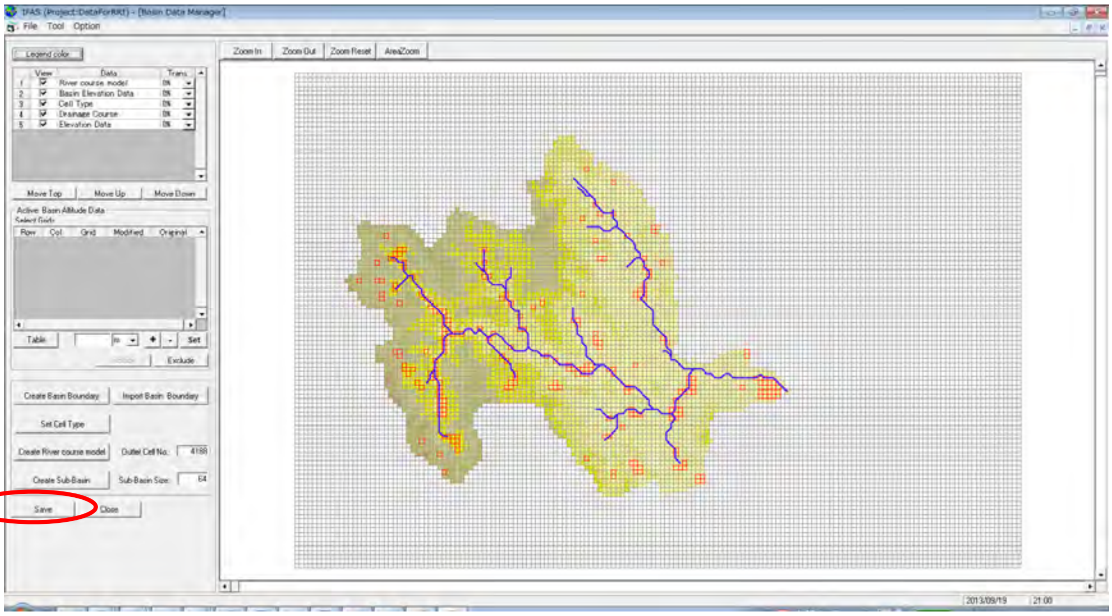
2. Click the outlet cell (River mouth).



C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Set the basin divide -8



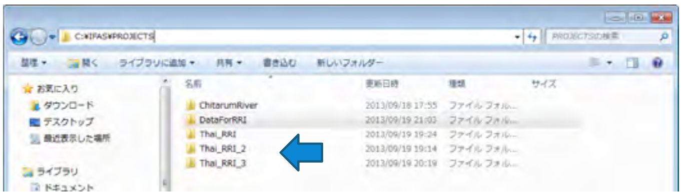
The work of IFAS is to here. Please save and close IFAS. After that, you can calculate runoff analysis if you set land use data, rainfall data and related parameters.

C. Practice of RRI Model

C-3) Preparing Input Topography Data

■ Edit ASCII: Topographic data obtained with IFAS have to be converted to RRI format according to following procedures.

1. Files you created with IFAS are stored in :C¥IFAS¥PROJECTS



2. Copy ASCII files (:C¥IFAS¥PROJECTS¥DataForRRI¥RIVER and :C¥IFAS¥PROJECT¥DataForRRI¥BASIN) , and paste them in RRI work holder: (.¥Desktop¥Practice_Of_RRI_Model¥Topography_Data_From_IFAS).

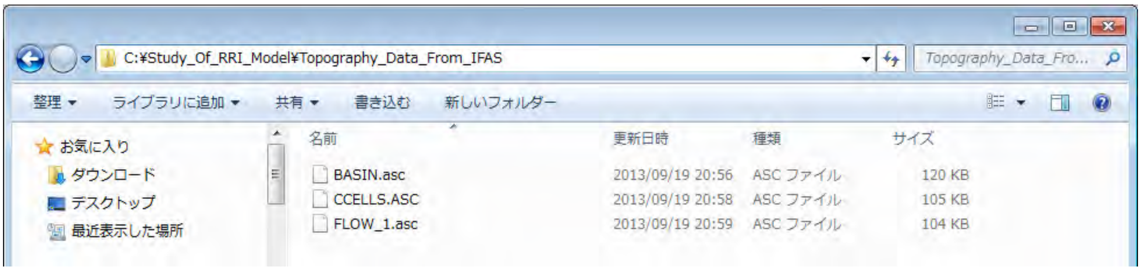
Copy 2 files「CCELLS.ASC」「FLOW_1.asc」 and Move them to (.¥Desktop¥Practice_Of_RRI_Model¥Topography_Data_From_IFAS)

Copy 1 file「BASIN.asc 」

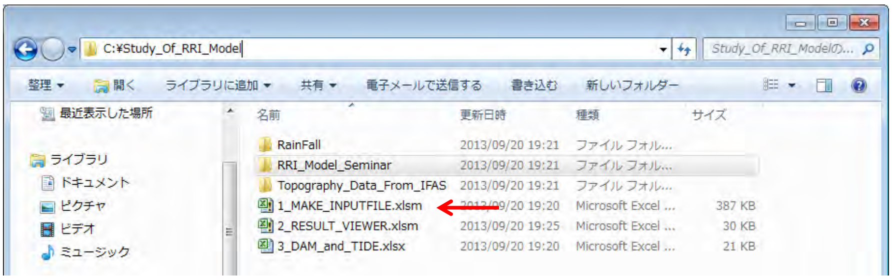
C. Practice of RRI Model

C-3) Preparing Input Topography Data

3. Save 3 ASCII files to
(.¥Desktop¥Practice_Of_RRI_Model¥Topography_Data_From_IFAS)



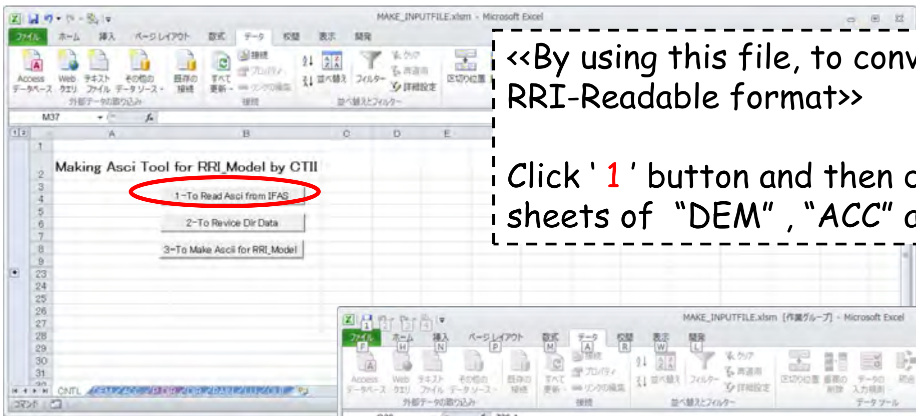
4. Open '1_MAKE_INPUTFILE.xlsm'



You can convert the ASCII files to RRI format!

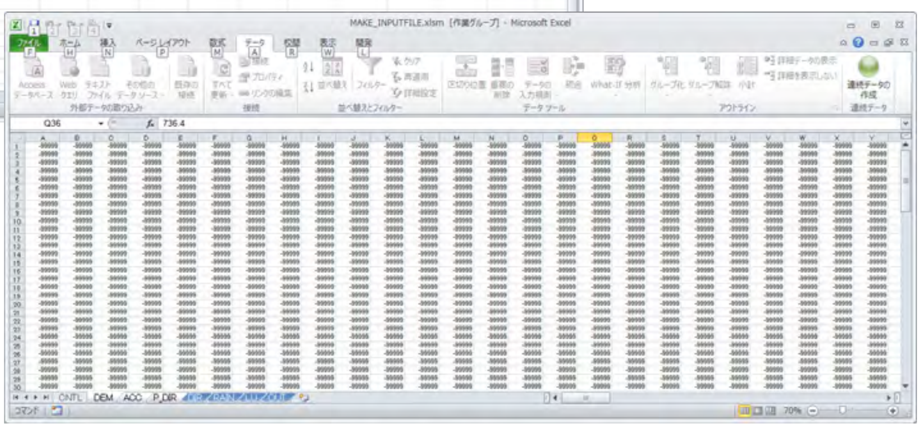
C. Practice of RRI Model

C-3) Preparing Input Topography Data



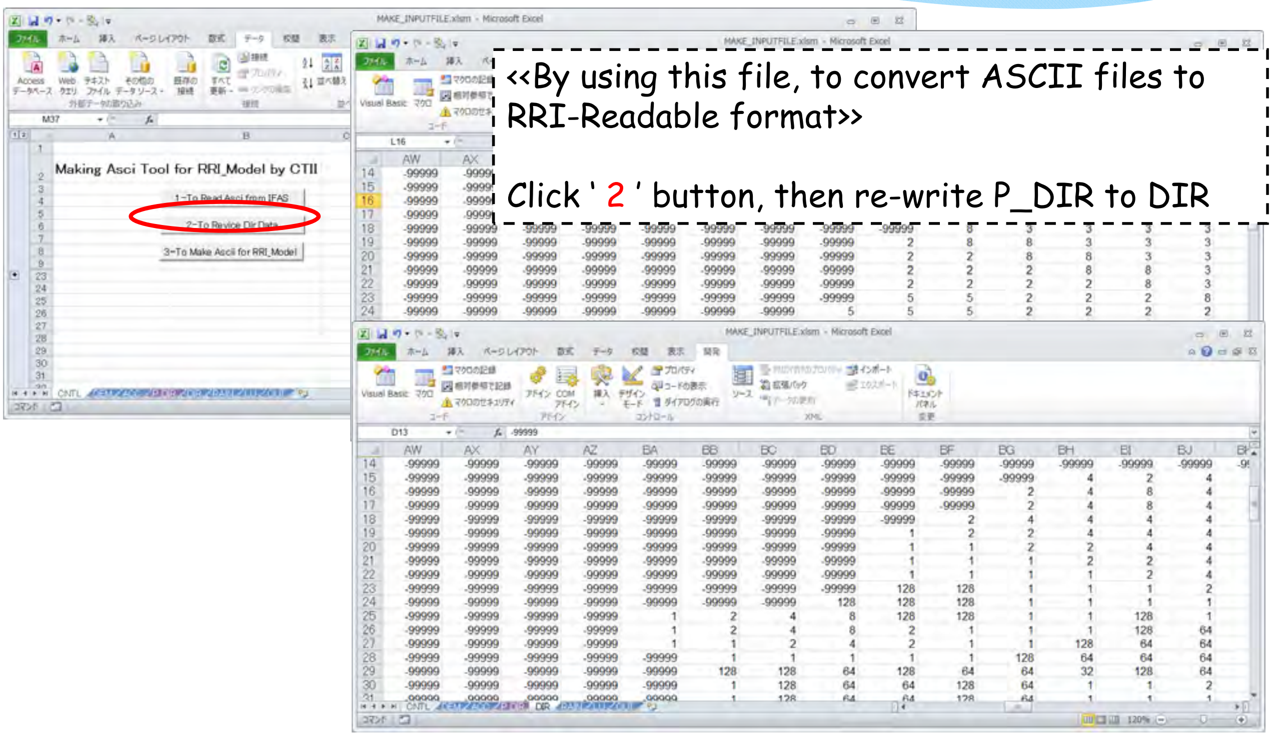
<<By using this file, to convert ASCII files to RRI-Readable format>>

Click ' 1 ' button and then data stick to the sheets of "DEM" , "ACC" and "P_DIR"



C. Practice of RRI Model

C-3) Preparing Input Topography Data

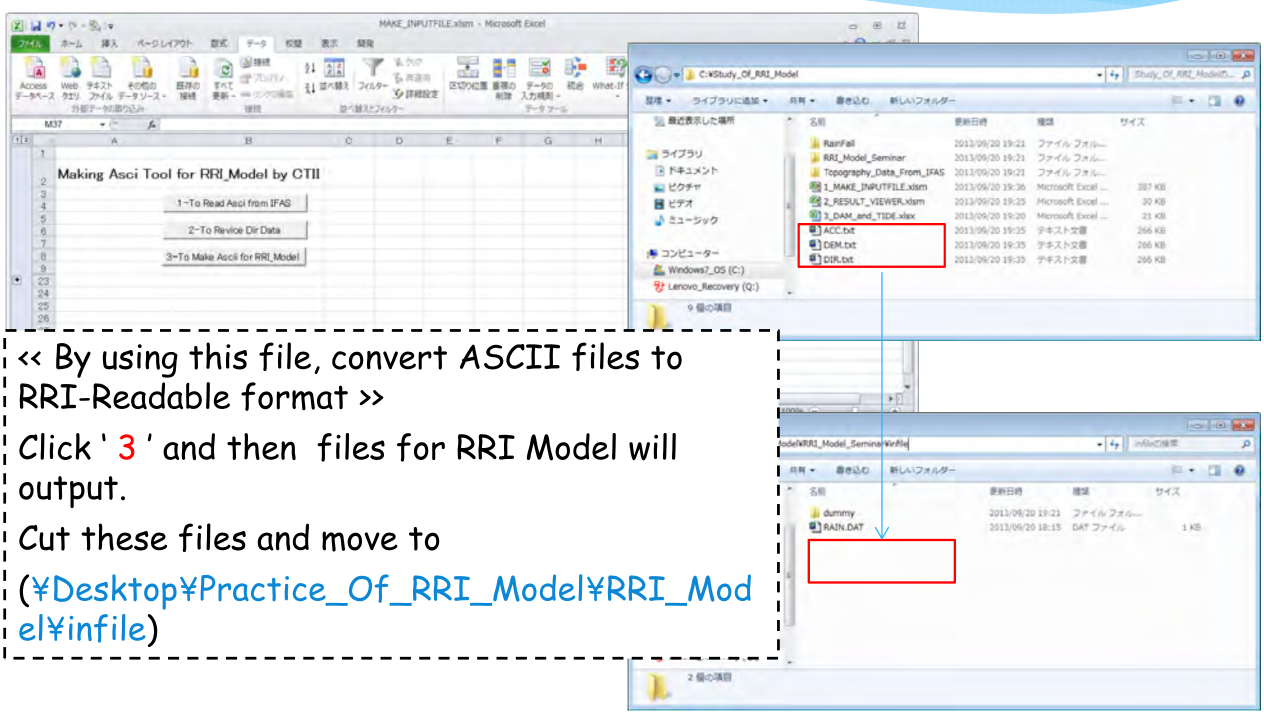


<<By using this file, to convert ASCII files to RRI-Readable format>>

Click ' 2 ' button, then re-write P_DIR to DIR

C. Practice of RRI Model

C-3) Preparing Input Topography Data



<< By using this file, convert ASCII files to RRI-Readable format >>

Click ' 3 ' and then files for RRI Model will output.

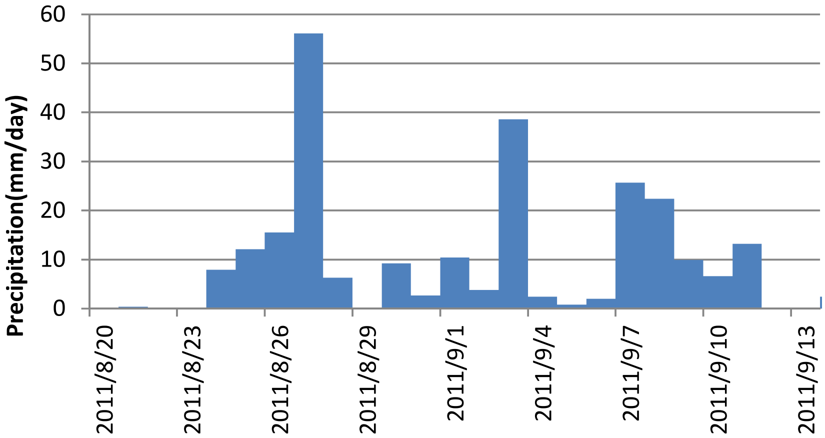
Cut these files and move to (¥Desktop¥Practice_Of_RRI_Model¥RRI_Model¥infile)

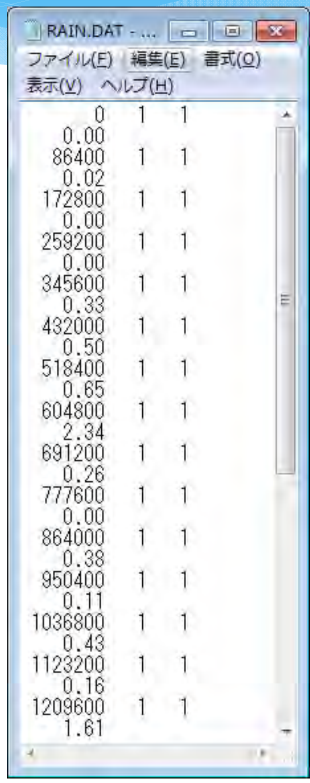
C. Practice of RRI Model

C-4) Preparing Input Rainfall data

■Sample rainfall data

Calculation period
2011/8/20~2011/9/13
(25days)
File name is "RAIN.DAT"



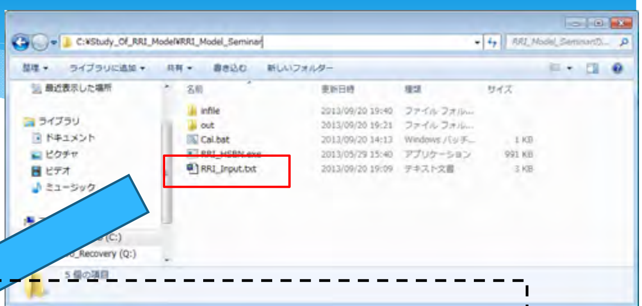


C. Practice of RRI Model

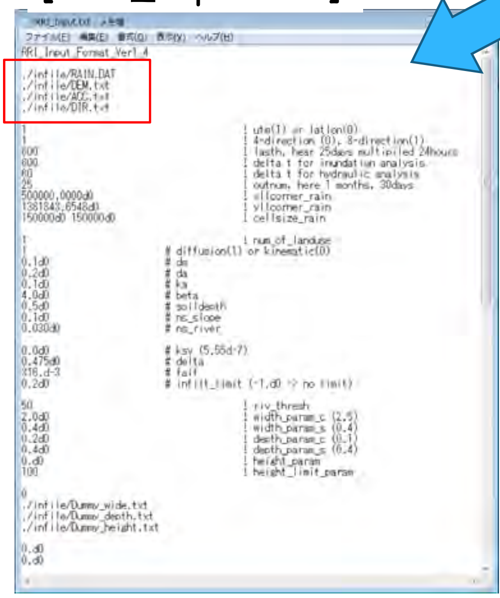
C-5) Execute RRI

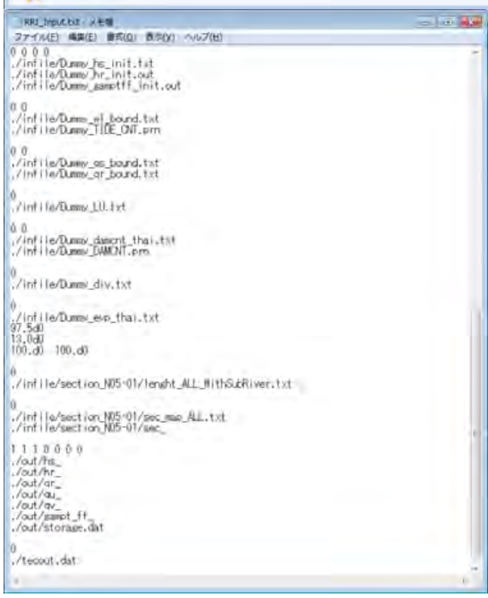
■Set "RRI_Input.txt" file

1. Check the file name.



[RRI_Input.txt]

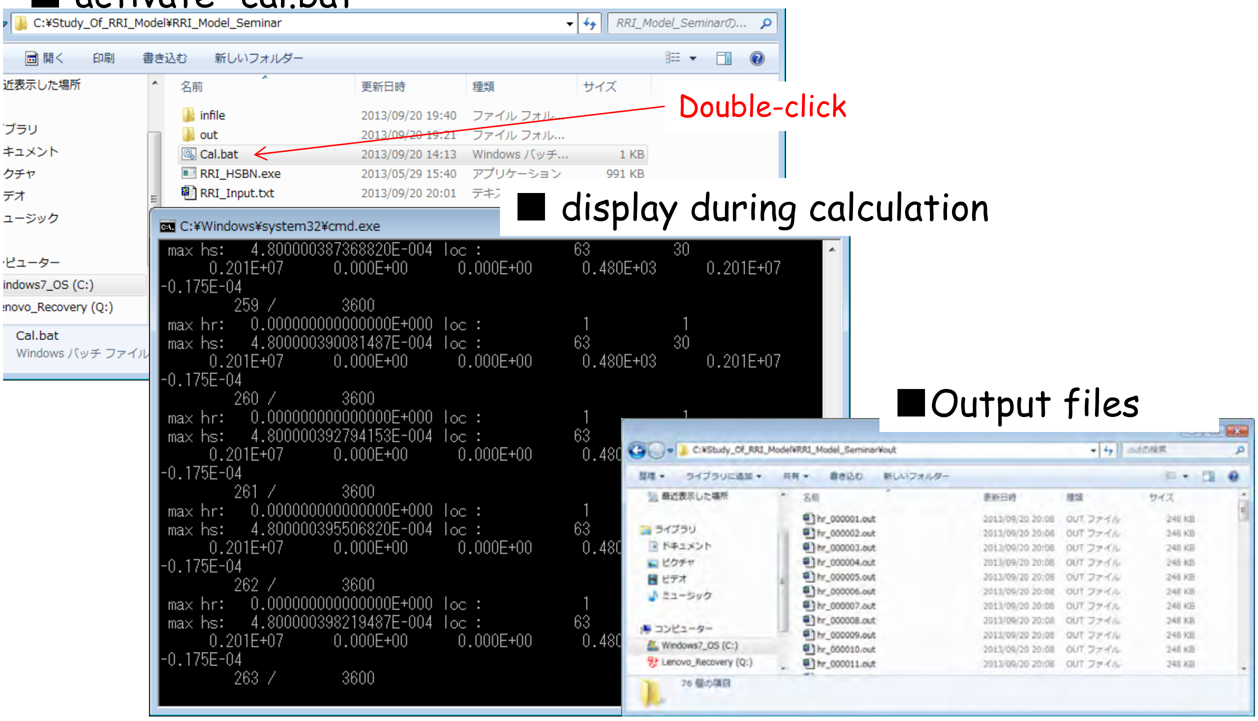




C. Practice of RRI Model

C-5) Execute RRI

■ activate "cal.bat"



C. Practice of RRI Model

C-6) View the Results

How to view the simulation results?

(1) Draw hydrographs with Excel

(2) Visualize Inundation Depth with GNUPLOT

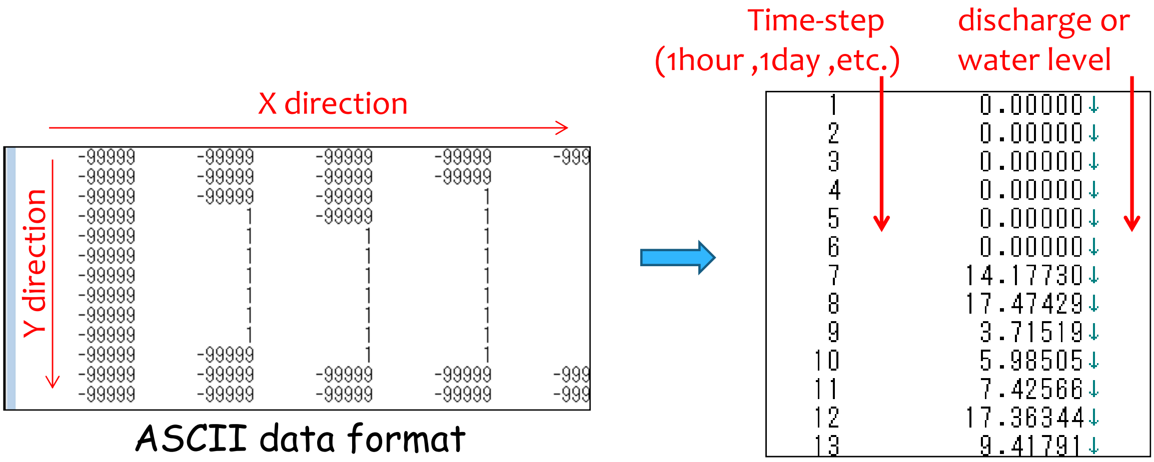
(3) Displaying Results on Google Earth

C. Practice of RRI Model

C-6) View the Results

(1) Draw time-series hydrographs with Excel

■ Preparation: Convert output data from ASCII to time-series format.



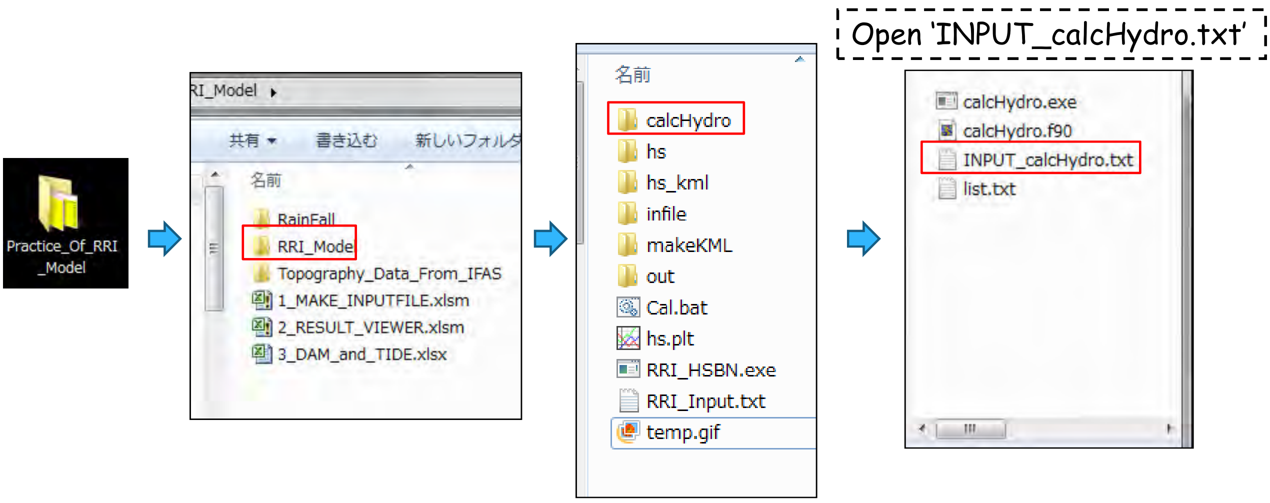
ASCII data format

time-series format

C. Practice of RRI Model

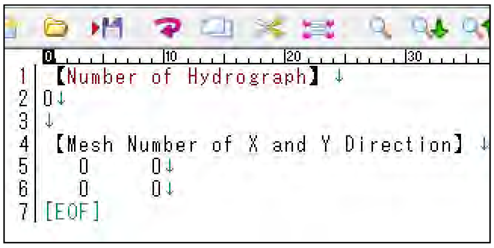
C-6) View the Results

■ Preparation: Convert output data from ASCII to time-series format.

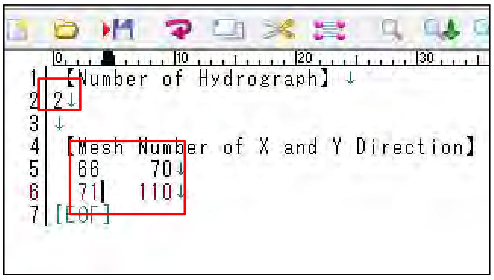


C. Practice of RRI Model

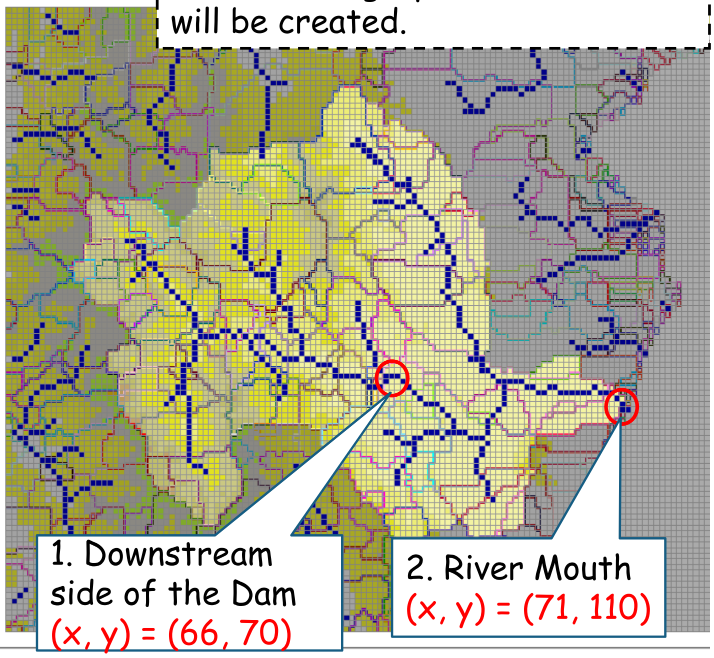
C-6) View the Results



Set Values



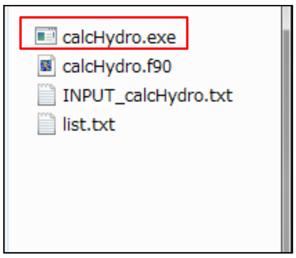
Time-series graph of 2 locations will be created.

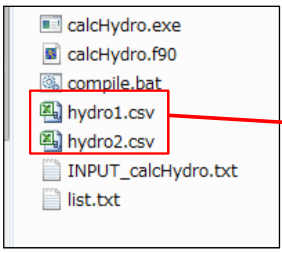


C. Practice of RRI Model

C-6) View the Results

Double-Click "calcHydro.exe"





Time-step (1 day) Discharge (m³/s)

8/20 0:00
8/21 0:00
8/22 0:00
:
:
:

	A	B
1	1	0
2	2	0
3	3	0
4	4	0
5	5	0
6	6	0
7	7	14.00606
8	8	18.21982
9	9	3.61561
10	10	5.55908
11	11	7.73884

"Hydro1.csv"
Time-series data of Discharge at Downstream side of the Dam.

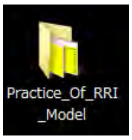
	A	B
1	1	0
2	2	0
3	3	0
4	4	0
5	5	0
6	6	0
7	7	45.54824
8	8	13.55839
9	9	2.46895
10	10	17.30551

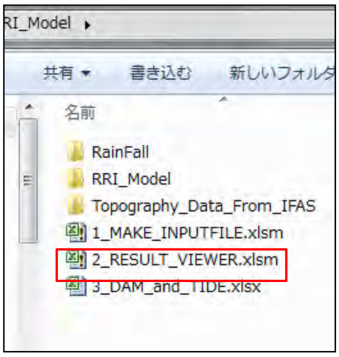
"Hydro2.csv"
Time-series data of Discharge at River Mouth.

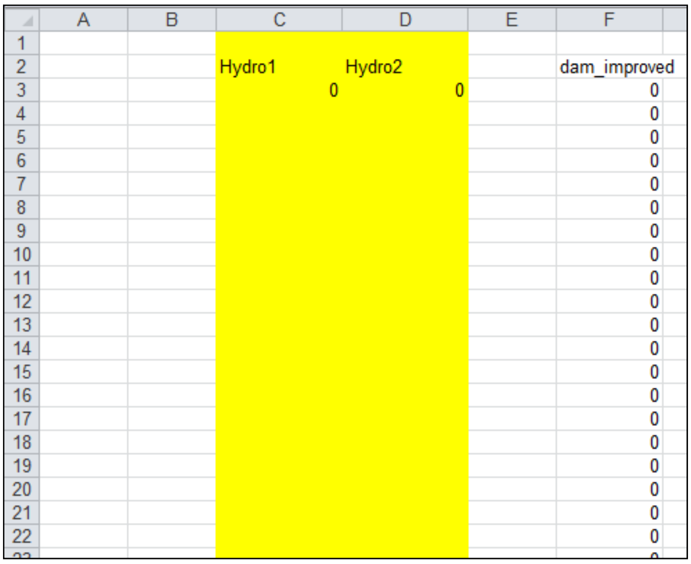
C. Practice of RRI Model

C-6) View the Results

Open 'RESULT_VIEWER.xlsm'





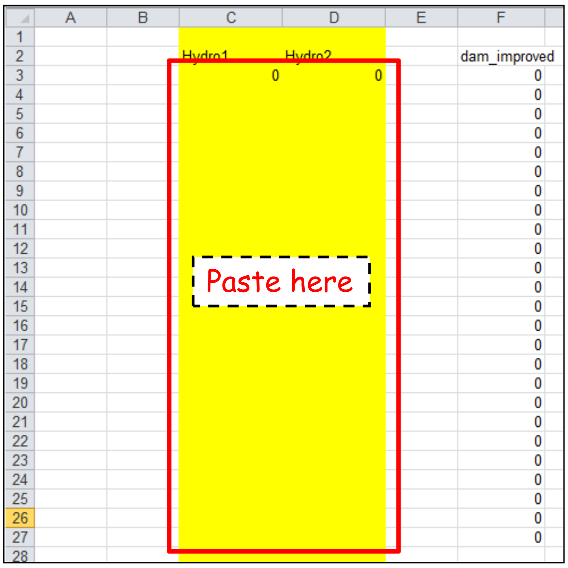


	A	B	C	D	E	F
1						
2			Hydro1	Hydro2		dam_improved
3			0	0		0
4						0
5						0
6						0
7						0
8						0
9						0
10						0
11						0
12						0
13						0
14						0
15						0
16						0
17						0
18						0
19						0
20						0
21						0
22						0

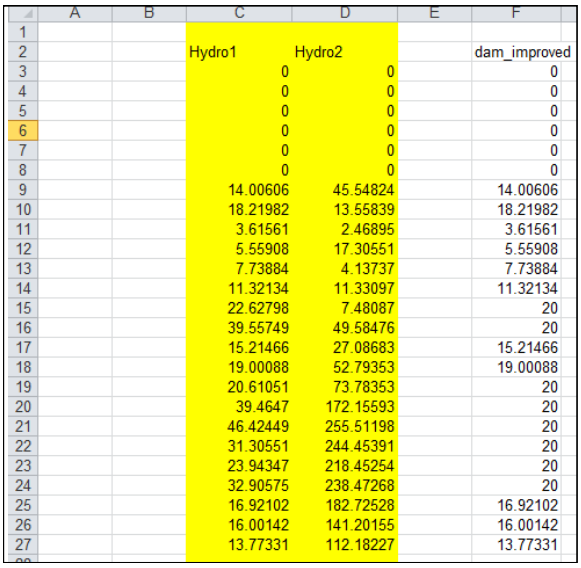
C. Practice of RRI Model

C-6) View the Results

Copy and Paste the Values of "Hydro1.csv" "Hydro2.csv" to "RESULT_VIEWER.xlsm"



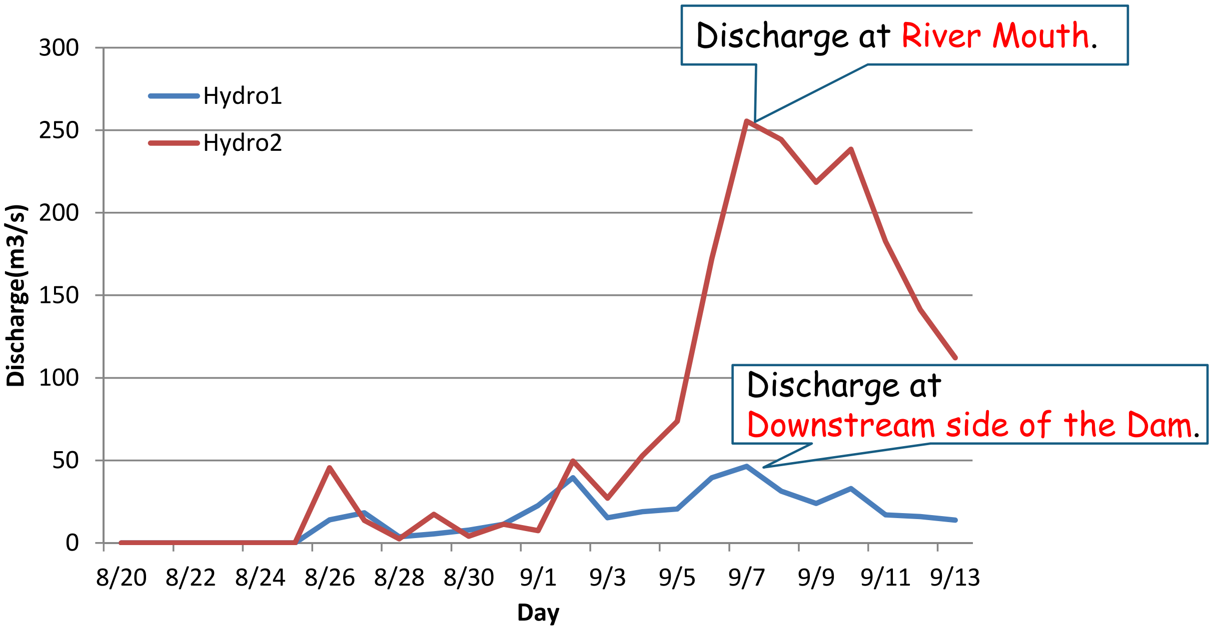
	A	B	C	D	E	F
1						
2			Hydro1	Hydro2		dam_improved
3			0	0		0
4						0
5						0
6						0
7						0
8						0
9						0
10						0
11						0
12						0
13						0
14						0
15						0
16						0
17						0
18						0
19						0
20						0
21						0
22						0
23						0
24						0
25						0
26						0
27						0
28						



	A	B	C	D	E	F
1						
2			Hydro1	Hydro2		dam_improved
3			0	0		0
4			0	0		0
5			0	0		0
6			0	0		0
7			0	0		0
8			0	0		0
9			14.00606	45.54824		14.00606
10			18.21982	13.55839		18.21982
11			3.61561	2.46895		3.61561
12			5.55908	17.30551		5.55908
13			7.73884	4.13737		7.73884
14			11.32134	11.33097		11.32134
15			22.62798	7.48087		20
16			39.55749	49.58476		20
17			15.21466	27.08683		15.21466
18			19.00088	52.79353		19.00088
19			20.61051	73.78353		20
20			39.4647	172.15593		20
21			46.42449	255.51198		20
22			31.30551	244.45391		20
23			23.94347	218.45254		20
24			32.90575	238.47268		20
25			16.92102	182.72528		16.92102
26			16.00142	141.20155		16.00142
27			13.77331	112.18227		13.77331

C. Practice of RRI Model

C-6) View the Results



C. Practice of RRI Model

C-6) View the Results

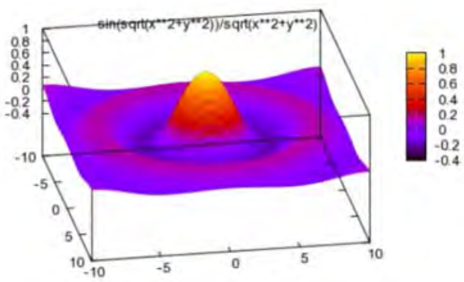
(2) Visualize Inundation Depth with GNUPLOT

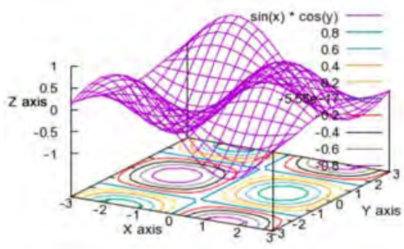
GNUPLOT is a graphing utility for MS Windows, Linux, and many other platforms.

The source code is copyrighted but freely distributed .

It was originally created to allow scientists and students to visualize mathematical functions and data.

GNUPLOT has been supported and under active development since 1986.





Sample Graphics of GNUPLOT (from GNUPLOT homepage)

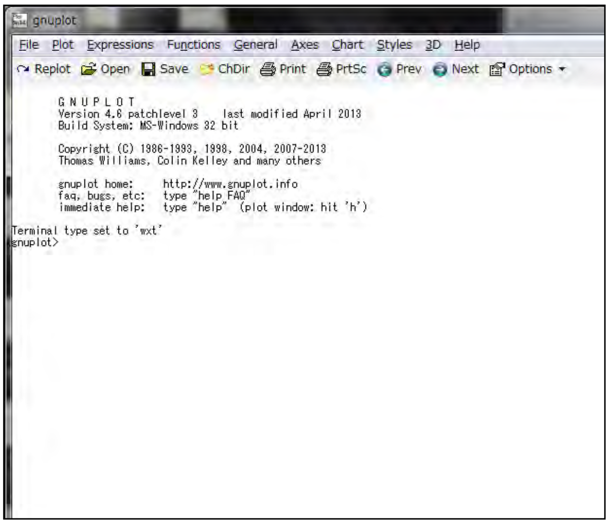
C. Practice of RRI Model

C-6) View the Results

Install GNUPLOT on your PC

1. Go to GNUPLOT HOMEPAGE (http://www.gnuplot.info/) and Download the Latest setup file.
2. Execute the XXX-SETUP.exe.
3. GNUPLOT will be installed.

Double-click "Gnuplot" Icon

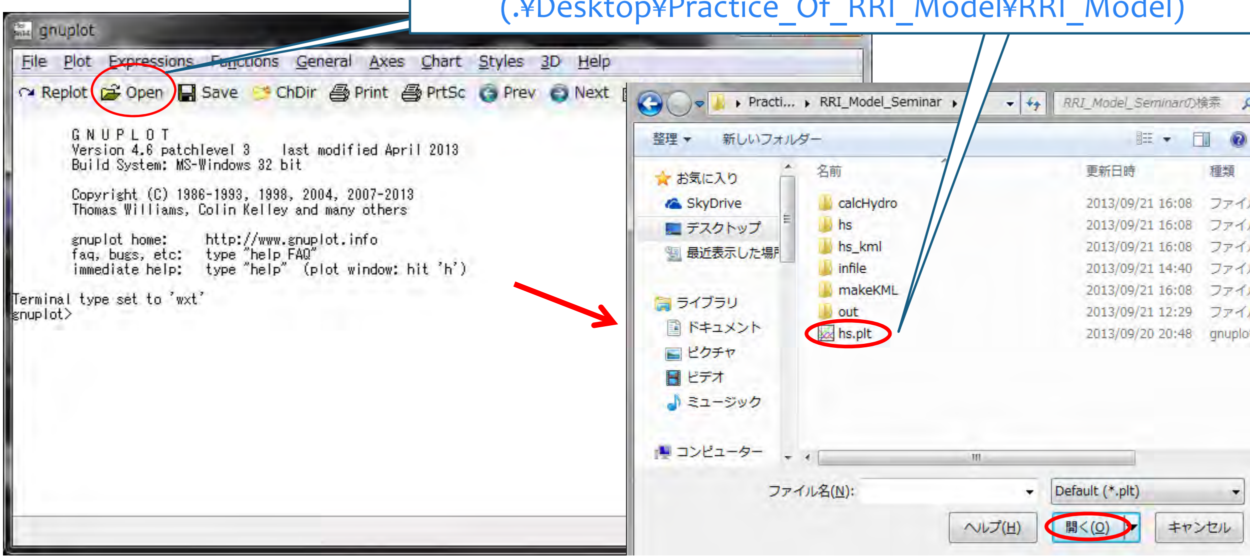


C. Practice of RRI Model

C-6) View the Results

GNUPLOT has a command-line driven graphing utility, so user can create flood inundation maps by reading "hs.plt", in which the command procedure (type of graph, size, color…) is written.

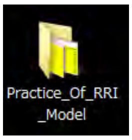
Open and Select file "hs.plt"
(.¥Desktop¥Practice_Of_RRI_Model¥RRI_Model)

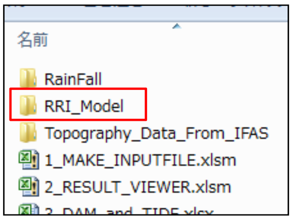


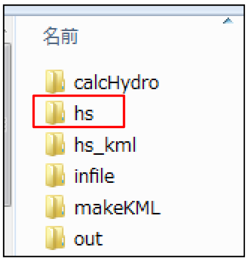
C. Practice of RRI Model

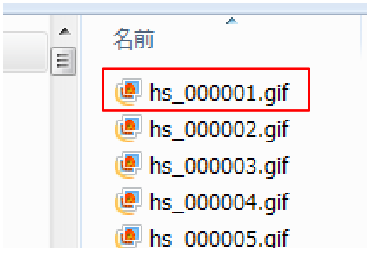
C-6) View the Results

Move to(.¥Desktop¥Practice_Of_RRI_Model¥RRI_Model¥hs)

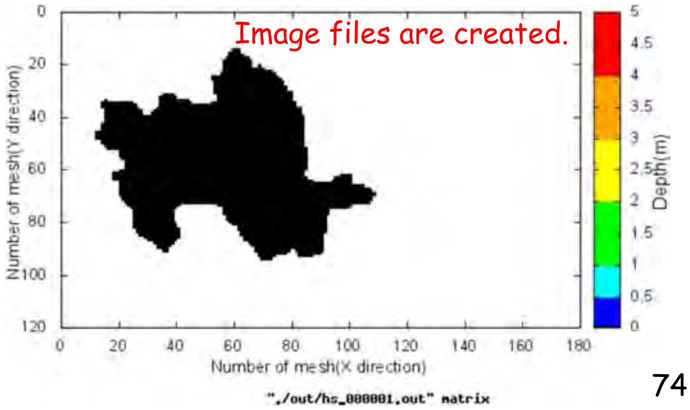








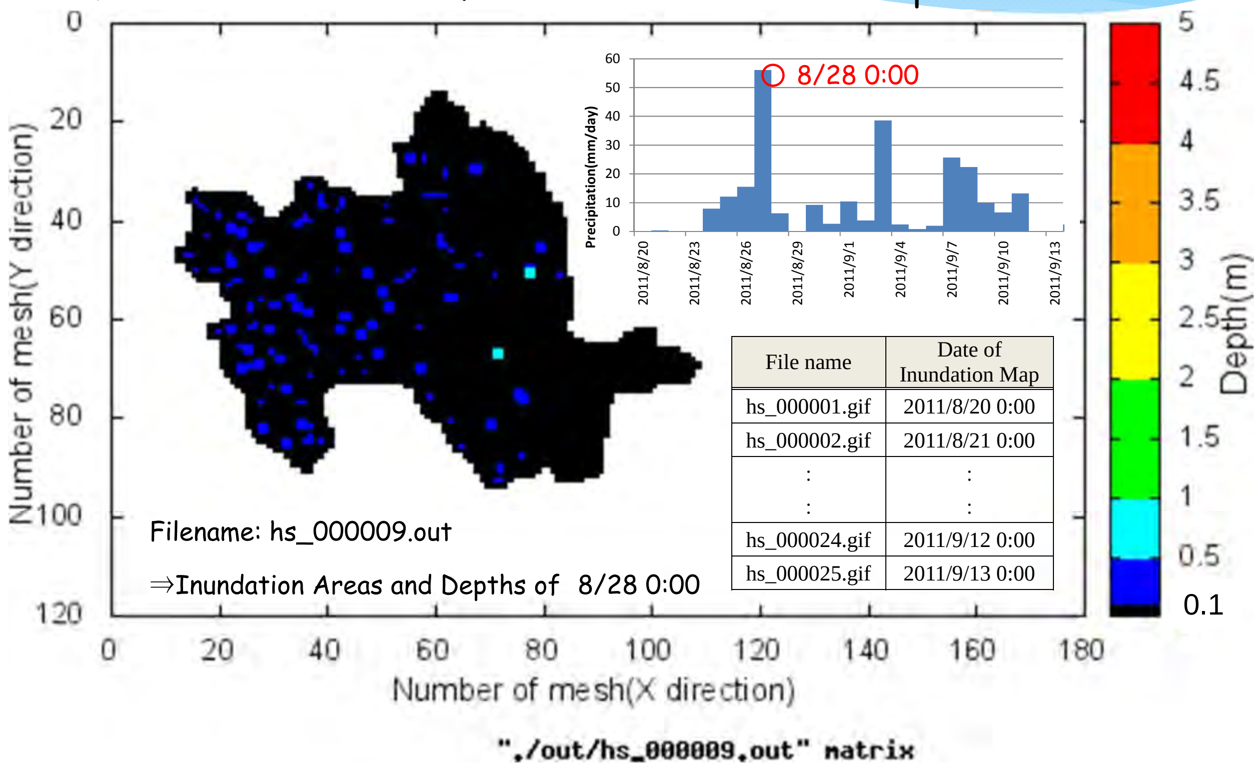
Click and Open "XXX.gif"



C. Practice of RRI Model

C-6) View the Results

Time-Series Variation of Inundation Areas and Depths.

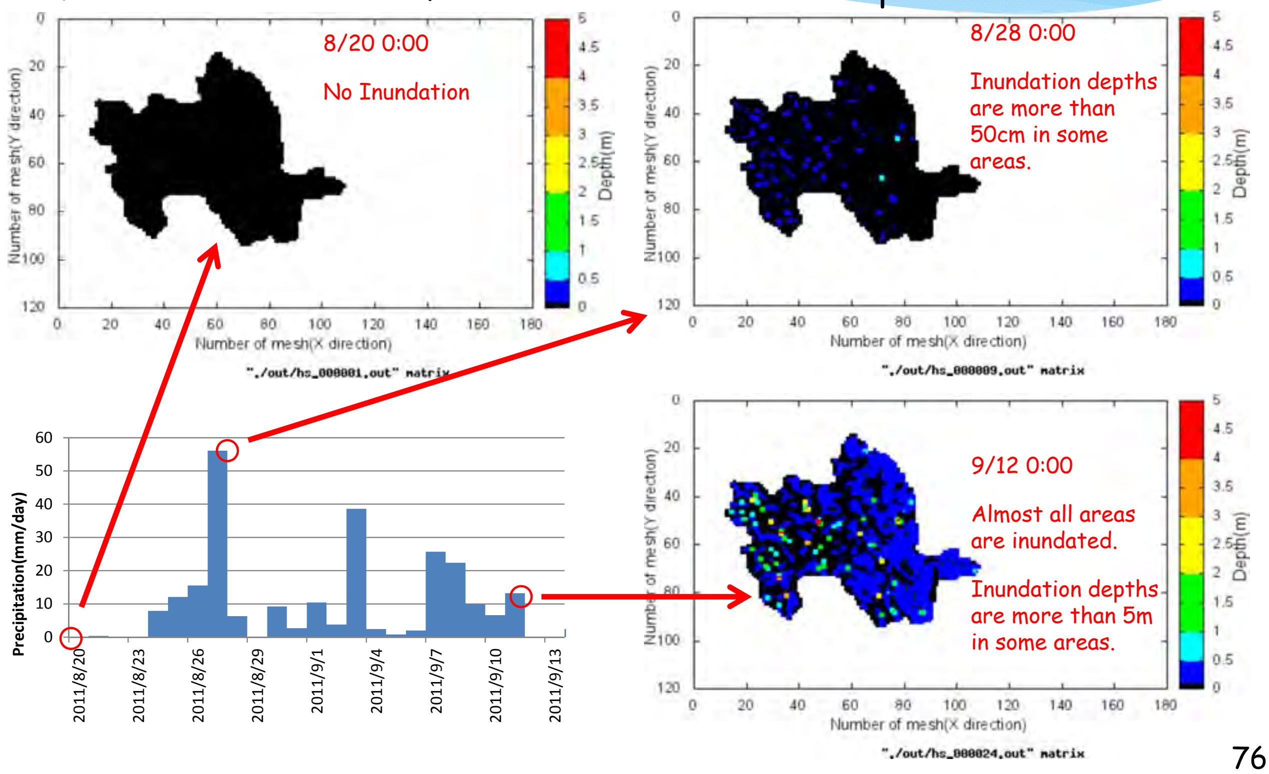


File name	Date of Inundation Map
hs_000001.gif	2011/8/20 0:00
hs_000002.gif	2011/8/21 0:00
:	:
:	:
hs_000024.gif	2011/9/12 0:00
hs_000025.gif	2011/9/13 0:00

C. Practice of RRI Model

C-6) View the Results

Time-Series Variation of Inundation Areas and Depths.



C. Practice of RRI Model

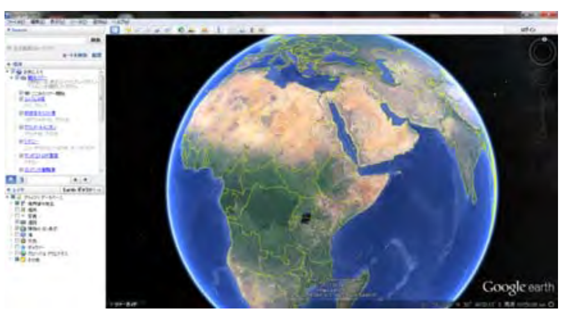
C-6) View the Results

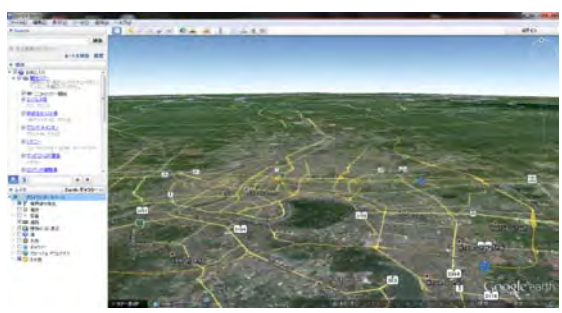
(3)Displaying Results on Google Earth

Google Earth is a virtual globe browser, arguably the most popular of those available for free via the Internet.

Virtual globes allow users to interactively display and investigate geographic data (primarily satellite and aerial images and terrain models, but also 2- and 3-D vector data such as earthquake locations, water bodies, and buildings).

One of the most useful aspects of Google Earth is the simplicity of visualizing the geological-related datasets.





C. Practice of RRI Model

C-6) View the Results

Prepare KML File

"*.KML" is a file that Google Earth can read and understand the procedure to do. It includes:

- Display Area (Latitude, Longitude)
- Start and End Date of Simulation
- Graphical File of Inundation to display on Google Earth.

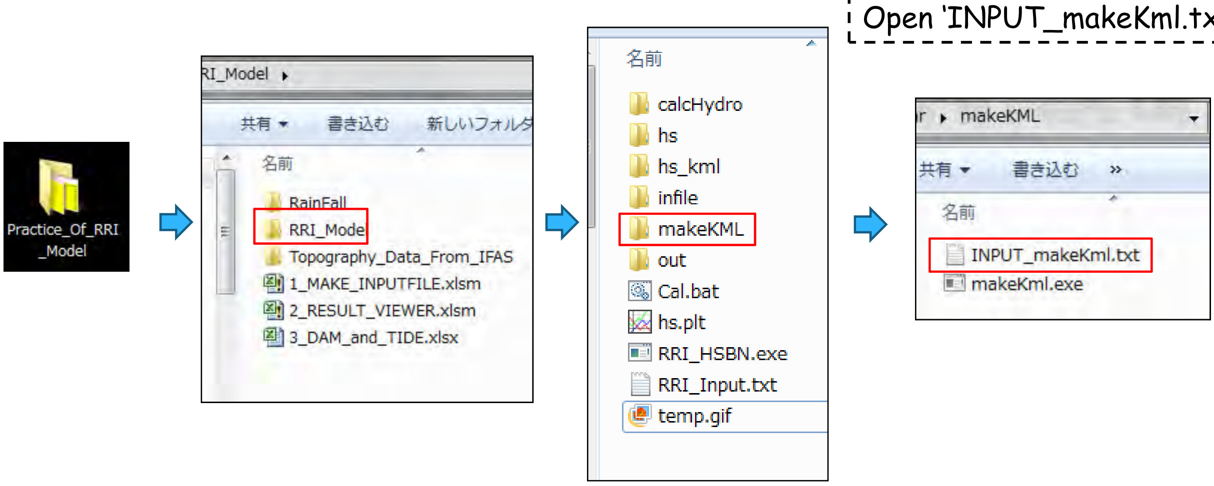
  (You have already created with Gnuplot)

C. Practice of RRI Model

C-6) View the Results

Prepare KML File

Open 'INPUT_makeKml.txt'

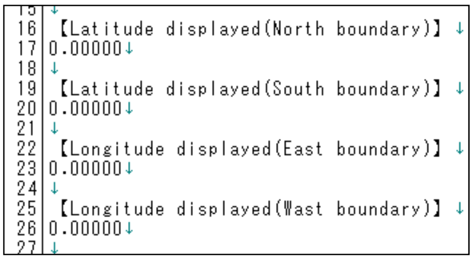


C. Practice of RRI Model

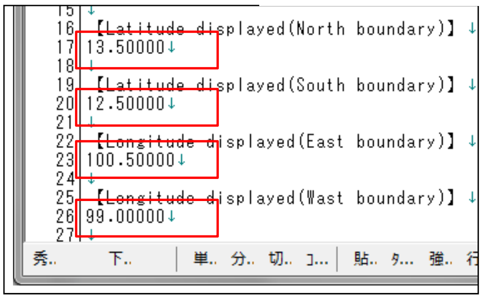
C-6) View the Results

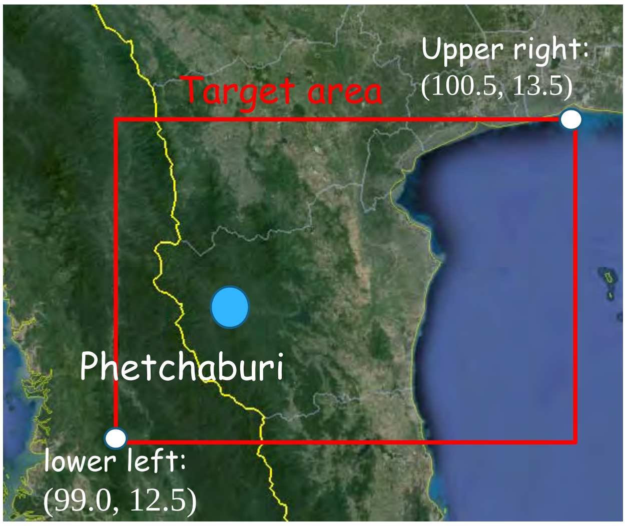
Prepare KML File

Input the boundary coordination of target area in "INPUT_makeKml.txt ".



Set coordination





C. Practice of RRI Model

C-6) View the Results

Prepare KML File

Execute "makeKML.exe" to create KML file.

• makeKML.exe was developed by CTI Engineering Co.,Ltd. http://www.ctie.co.jp/2012rn/index.html

C. Practice of RRI Model

C-6) View the Results

Prepare KML File

User can check contents of KML file with text editor (example, notepad and MIFES etc…).

```
<Folder>↓
 <GroundOverlay>↓
  <TimeSpan>↓
   <begin>2011-08-20T00Z</begin>↓
   <end>2011-08-21T00Z</end>↓
  </TimeSpan>↓
  <Icon>↓
   <href>..¥hs_kml¥hs_kml000001.tgif</href>↓
  </Icon>↓
  <LatLonBox>↓
   <north>13.50000</north>↓
   <south>12.50000</south>↓
   <east>100.50000</east>↓
   <west>99.00000</west>↓
  </LatLonBox>↓
 </GroundOverlay>↓
 <GroundOverlay>↓
  <TimeSpan>↓
   <begin>2011-08-21T00Z</begin>↓
   <end>2011-08-22T00Z</end>↓
```

Information about time

Information about Image File. (already created)

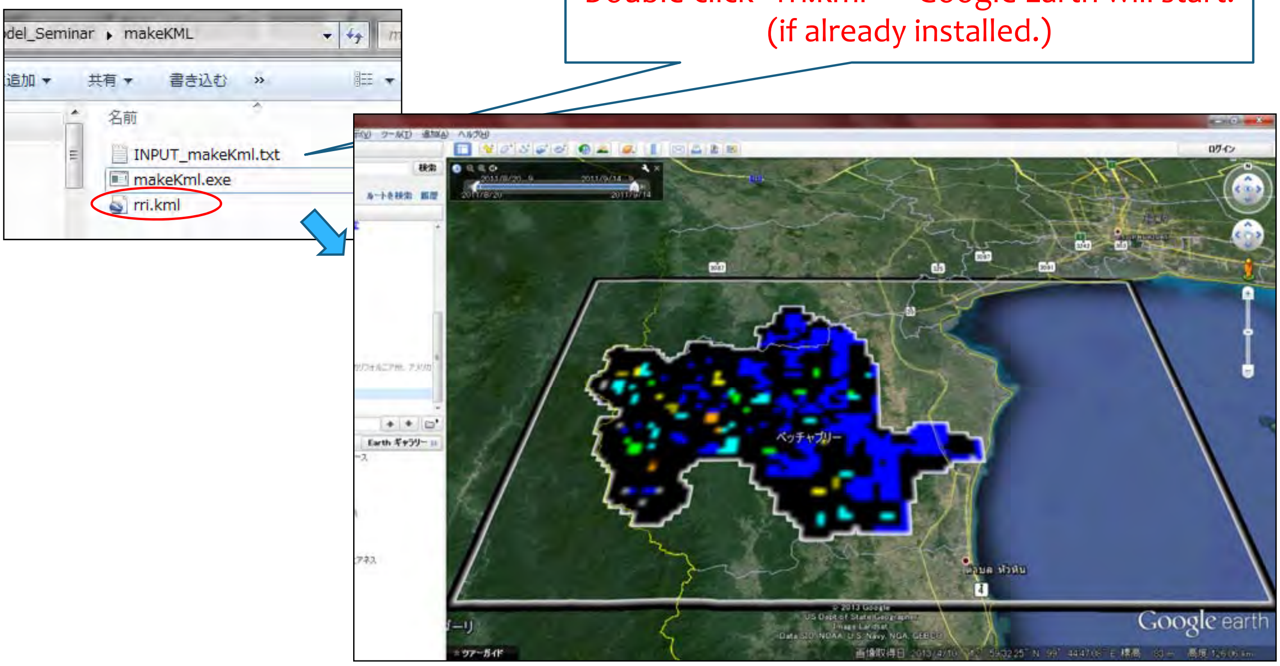
Information about Latitude, Longitude displayed.

C. Practice of RRI Model

C-6) View the Results

Displaying on Google Earth.

Double-click "rri.kml"⇒Google Earth will start. (if already installed.)



C. Practice of RRI Model

C-6) View the Results

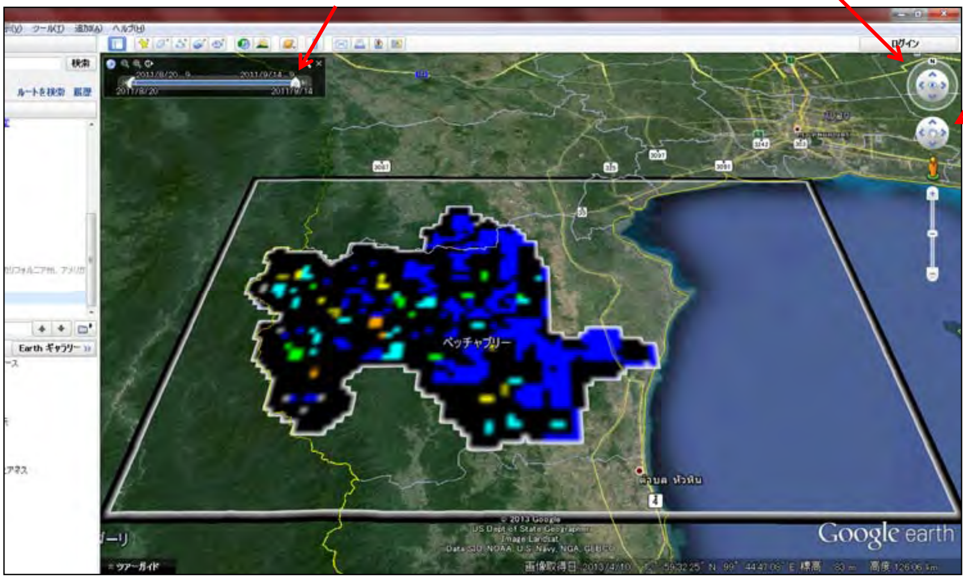
Displaying on Google Earth

Time series:
Move the range marker to right or left.

Rotate View Angle:

Move view

Zoom up or down



C. Practice of RRI Model

C-6) View the Results

Displaying on Google Earth

User can find with Google Earth:

- ☐ High-risk flood area.
- ☐ Duration of inundation (information for land use)
- ☐ Relatively safe zone or evacuation route. (information for evacuation)

, etc..

Advantages by using "Google Earth"

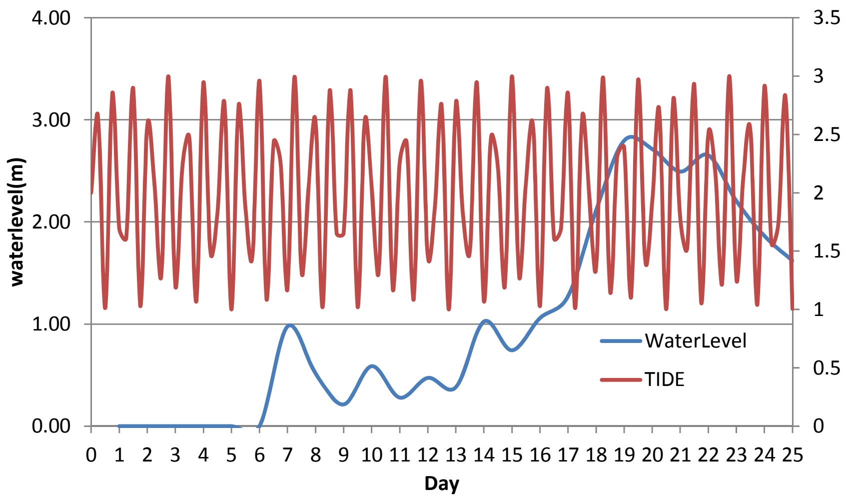
- User can utilize continuously updated information, such as aerial photograph, buildings, road.
- Get for free.
- Internet-active condition is only that user have to prepare. No other tools or files (large size global map etc…) are needed.

C. Practice of RRI Model

C-7) Try Simulations with Additional Conditions

(1) Change downstream boundary condition "input tidal data"

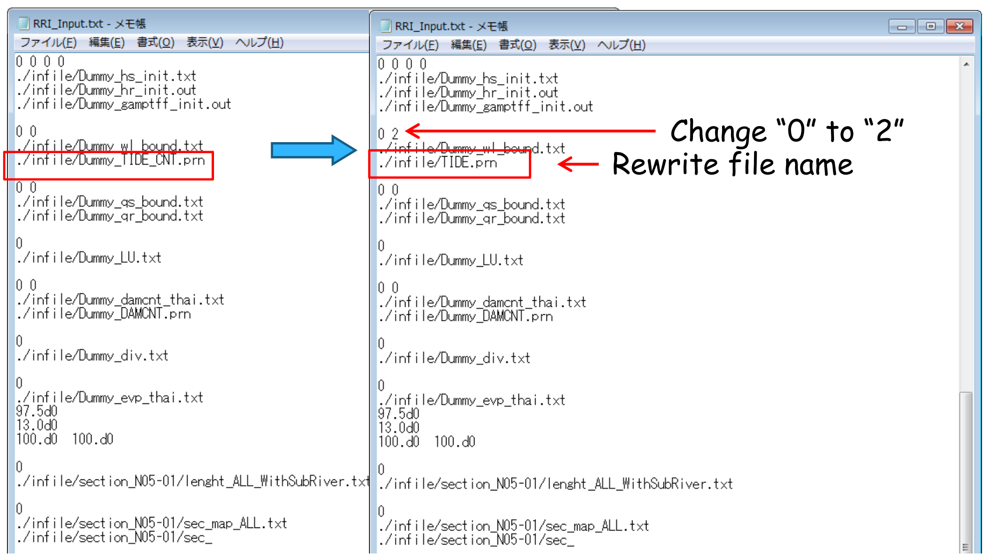
1. Open "3_DAM_and_TIDE.xlsx" file
2. Input tidal data as boundary condition of the end of steam. Mesh position is (71,110)



C. Practice of RRI Model

C-7) Try Simulations with Additional Conditions

3. Set "TIDE.prn" file



Please Check the Result!

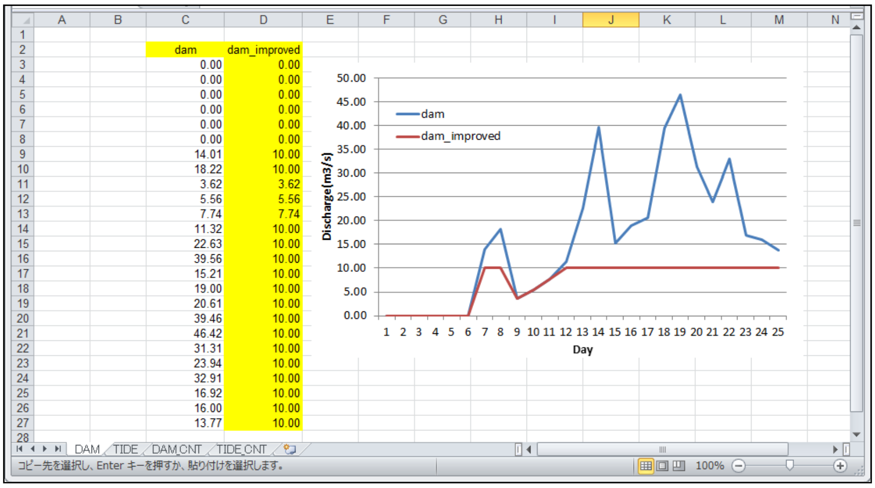
C. Practice of RRI Model

C-7) Try Simulations with Additional Conditions

(2) Change upstream boundary condition "input dam release data"

1. Open "3_DAM_and_TIDE.xlsx" file

2. Input Outflow data as boundary condition(66,70)

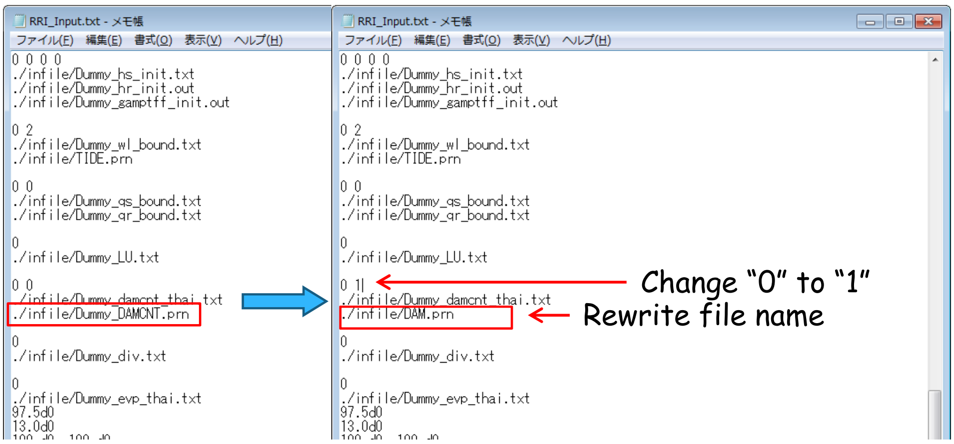


	dam	dam_improved
3	0.00	0.00
4	0.00	0.00
5	0.00	0.00
6	0.00	0.00
7	0.00	0.00
8	0.00	0.00
9	14.01	10.00
10	18.22	10.00
11	3.62	3.62
12	5.56	5.56
13	7.74	7.74
14	11.32	10.00
15	22.63	10.00
16	39.56	10.00
17	15.21	10.00
18	19.00	10.00
19	20.61	10.00
20	39.46	10.00
21	46.42	10.00
22	31.31	10.00
23	23.94	10.00
24	32.91	10.00
25	16.92	10.00
26	16.00	10.00
27	13.77	10.00

C. Practice of RRI Model

C-7) Try Simulations with Additional Conditions

3. Set "DAM.prn" file



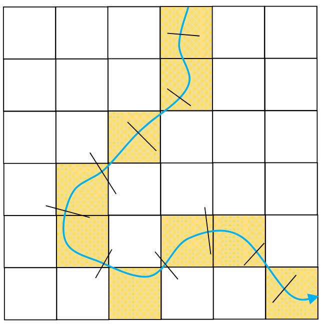
Please Check the Result!

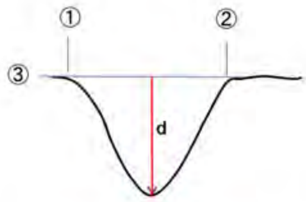
C. Practice of RRI Model

C-8) Others

(1) Input cross-sectional property

In RRI Model (version 1.4β), user can calculate water level and discharge considering actual cross section. Cross-sectional property can be given to each calculation grid, which expects high-accuracy simulation.

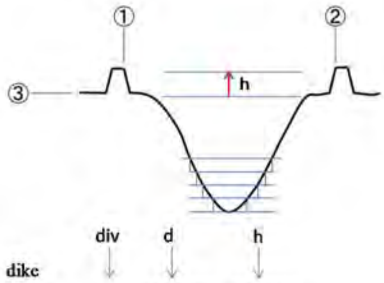




STEP1: Measurement of river depth (d) and dike height from ground (h)

STEP2: Divide the length from lowest river bed to top of the dike (example: 100)

STEP3: Wetted perimeter, surface water width and representative roughness coefficient according to divided water depth is calculated.



div d h

100	10.98000	0.00000	
0.11339	23.78646	23.77967	0.03000
0.22678	27.57293	27.55933	0.03000
0.34017	31.35939	31.33900	0.03000
0.45356	35.14586	35.11867	0.03000
Skip…			
11.11222	298.35455	295.76846	0.03000
11.22561	298.56949	295.95105	0.03000
11.33900	300.62881	298.00000	0.03000
Water depth	Wetted perimeter	Surface water width	River roughness coefficient

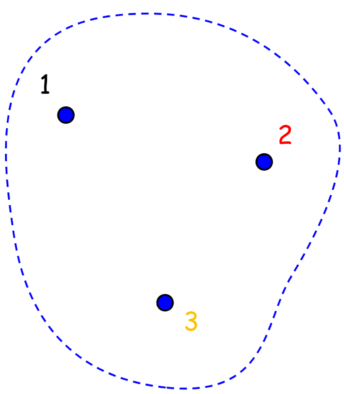
Sample of input format on cross sectional property

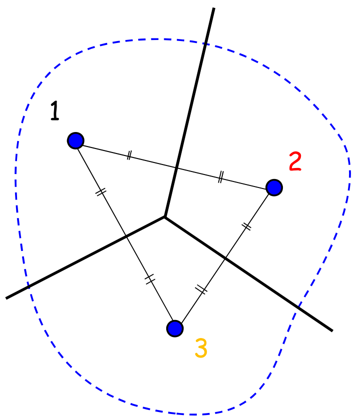
C. Practice of RRI Model

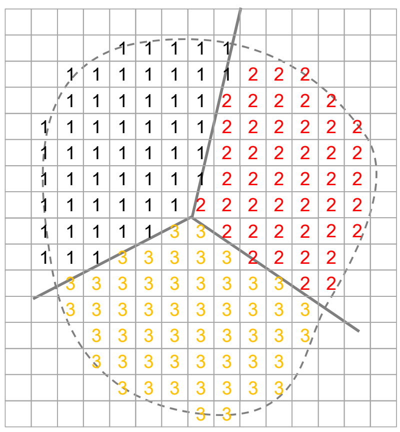
C-8) Others

(2) 2-dimensional rainfall distribution

RRI is available to use a two-dimensional rainfall data. Generally, "Thiessen polygon method (shoreline movement)" is employed to make 2-dimensional rainfall data as following,







● : Rainfall station
--- : River basin boundary

To identify coverage of each rainfall station with "Thiessen polygon method"

To prepare 2-dimensional distribution rainfall data with ASCII format (*.asc)

As other method, Isohyetal line method is used for making two-dimensional rainfall distribution.

D. How to get the RRI Model

D-1) Procurement of RRI Programs (coded with Fortran 90/95)

ICHARM and related agencies/institutes are considering, to whom and how to deliver RRI program codes, as of September 2013.

D-2) About Technical Support

ICHARM and related agencies/institutes are considering how to provide technical supports about RRI Model to users, as of September 2013.

Thank you for your attentions !