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A virtual GIS-based hydrodynamic model system for Tamshui River

Shin-Jye Liang and Frank Molkenthin

ABSTRACT

A computer infrastructure which integrates the geographic information system (GIS), hydrodynamic model, visualization and network applications was developed and applied in Tamshui River, Taiwan. A digital terrain model (DTM) of the study area was first generated. We used it as a basis to construct the computation grids, conduct the flow simulations, and visualize the predicted flow scenarios in the virtual world. The three-dimensional hydrodynamic and water quality model system WQMAP was employed to simulate flows under the tidal forcing, upstream river inflows and seawater–freshwater interactions of Tamshui River. Model predictions were generally in good agreement with other simulations. Computed results were visualized in both the innovative virtual reality (VR) environment and Internet-based collaborative visualization environment (CVE). The VR environment enabled us to observe firsthand the complicated flow phenomena in the virtual world. Internet-based CVE supports distributed visualization and collaboration. The GIS-based system exhibits great potential in data visualization capabilities and the improvement of water management. We anticipate that these computer technologies will popularly be applied to hydroinformatics and other related domains in the foreseeable future.

Key words | geographic information system, hydrodynamic modeling, scientific visualization, Virtual Reality, networked visualization, hydroinformatics, WWW-based collaboration

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INTRODUCTION

Tamshui River estuary in the northwest of Taiwan is the largest estuarine system of the island. It passes metropolitan Taipei, which is the centre of politics, economy and culture of Taiwan. The Tamshui River consists of three major tributaries: Tahan Stream, Hsintien Stream and Keelung River, as illustrated in Figure 1.

The river system has a total drainage area of 2,726 km^2 and a total channel length of 327.6 km. The river is relatively narrow with a width ranging from 500 to 1,500 m. The water depth ranges from 2–22 m and the average depth is 5 m. The river is 1,500 m wide with a depth of 3–22 m at the mouth of the river, and becomes narrow upstream, about 750 m with depth 2–15 m, at the Kuandu area. The downstream reaches of all three tributaries are influenced by tides. The upstream reaches are affected by daily varying freshwater inflows. Some hydraulic characteristics of Tamshui River are shown in Table 1 (Hsu *et al*. 1999; Liu *et al*. 2000).

The dynamic processes of the Tamshui estuary involve interactions between the tidal currents, upstream river inflow and seawater intrusion. They lead to a series of distinctive types of estuarine circulation and vertical salinity stratification. Circulation of the river is dominated by the lunar semi-diurnal tide (M_2: 12.42 h period). Maximum flow current magnitudes are typically 125–250 cm/s depending on location, with the highest current speeds near the Kuandu area.

Owing to the dense population and rapid economic development, poor quality water, air and soil pose a threat to public health during regular seasons in the study area.

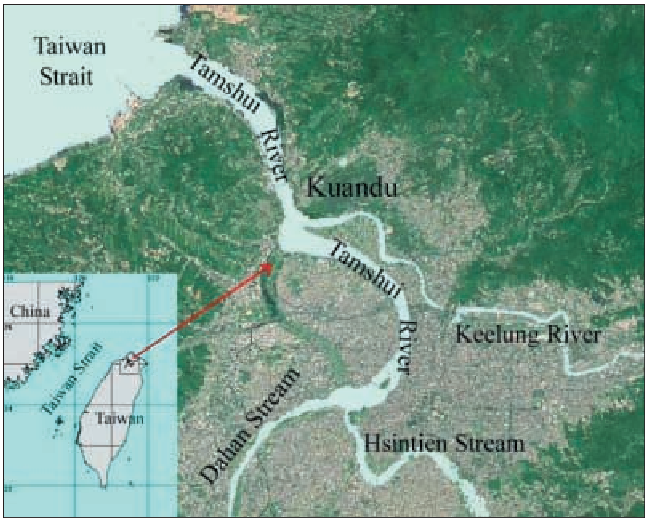

Figure 1 | Area of study—Tamshui River Basin.

Table 1 | Hydraulic characteristics of Tamshui River

	Length (km)	Drainage area (km^2)	Rainfall/year (mm/yr)	Yearly river inflow/s (m^3/s)
Hsintien Stream	84.6	916	3251	228.12
Tahan Stream	135	1163	2430	142.65
Keelung River	87	501	3969	36.88

Furthermore, inundations and mudslides often cause death and loss of property during the seasons of typhoon and heavy rain. Public concern over these situations have prompted the current study. Much research has been conducted previously to investigate the hydrodynamic and water quality of the river, such as Hsu *et al*. (1999) and Liu *et al*. (2000). We have also conducted a series of numerical studies of the hydrodynamics of the Tamshui River under tidal forcing, upstream inflow and seawater intrusion conditions (Liang *et al*. 1999*a*, *b*, 2000). The computed results agreed favorably with the simulated results by Hsu *et al*. (1999) and Liu *et al*. (2000).

Visualization is an important technology and powerful tool to explore data and present information (Brown *et al*. 1995). One of the purposes of the present study is to develop visualization tools for visualizing and analyzing the computed data in a distributed environment. Various visualization tools, including virtual reality (VR) and collaborative visualization environment (CVE), were developed to explore model predictions in the virtual digital world. These advanced visualization technologies provide us with an insight into the surrounding environment and associated physics, and the potential benefits of distributed visualization and collaboration.

HYDRODYNAMIC MODEL

Using a spherical coordinate system, where ϕ is the longitudinal positive east, θ is the latitude positive north and r is the radius of Earth positive up, the equations of continuity, momentum, and conservation of substance, and state of the seawater can be written as

Continuity

$$\frac{1}{r\cos\theta}\frac{\partial u}{\partial\phi}+\frac{1}{r}\frac{\partial v}{\partial\theta}-\frac{v}{r}\tan\theta+\frac{1}{r^2}\frac{\partial r^2 w}{\partial r}=0 \tag{1}$$

Momentum

$$\frac{\partial u}{\partial t}+\frac{u}{r\cos\theta}\frac{\partial u}{\partial\phi}+\frac{v}{r}\frac{\partial u}{\partial\theta}-\frac{uv}{r}\tan\theta+w\frac{\partial u}{\partial r}+\frac{uw}{r}-fv =-\frac{1}{\rho_0 r\cos\theta}\frac{\partial p}{\partial\phi}+\frac{\partial}{\partial r}\left(A_v\frac{\partial u}{\partial r}\right) \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{u}{r\cos\theta}\frac{\partial v}{\partial\phi}+\frac{v}{r}\frac{\partial v}{\partial\theta}+\frac{uu}{r}\tan\theta+w\frac{\partial v}{\partial r}+\frac{vw}{r}-fu =-\frac{1}{\rho_0 r\cos\theta}\frac{\partial p}{\partial\theta}+\frac{\partial}{\partial r}\left(A_v\frac{\partial v}{\partial r}\right) \tag{3}$$

$$\frac{\partial p}{\partial r}=-\rho g \tag{4}$$

Conservation of substance

$$\frac{\partial q}{\partial t}+\frac{u}{r\cos\theta}\frac{\partial q}{\partial\phi}+\frac{v}{r}\frac{\partial q}{\partial\theta}+w\frac{\partial q}{\partial r} =\frac{\partial}{\partial r}\left[D_v\left(\frac{\partial q}{\partial r}\right)\right]+\frac{D_h}{r^2}\left[\frac{\partial^2 q}{\cos^2\partial\phi^2}+\frac{\partial^2 q}{\partial\theta^2}\right] \tag{5}$$

Equation of state of seawater

$$\rho = f(S, \Theta) \quad (6)$$

where t = time; u, v and w = velocity components in ϕ, θ, and r, respectively; f = Coriolis parameter; p = pressure; g = gravity; $\boldsymbol{\rho}$ = water density; $\boldsymbol{\rho}_0$ = basin-averaged water density; A_v = vertical eddy viscosity; D_v = vertical eddy diffusivity; D_h = horizontal eddy diffusivity; Θ = temperature (°C); S = salinity (ppt); and q = concentration of a conservative substance such as Θ and S.

WQMAP (ASA 1999) was employed to simulate flows under tidal forcing, upstream river inflows and seawater intrusions in Tamshui River. WQMAP is a three-dimensional, unsteady, hydrodynamic and transport model system for coastal and estuarine waters. It solves the above three-dimensional shallow-water equations using a boundary-fitted and δ-coordinates finite-difference method. The model uses a split mode technique where the equations are decomposed into exterior and interior modes (Madala & Piacsek 1977). The exterior mode (vertically averaged) is solved using a semi-implicit solution scheme, whereas the interior mode (vertical structure) is solved explicitly, except for the vertical diffusion terms, which are solved implicitly. More detailed information on the governing equations and numerical solution methodology and model applications could be found in Muin & Spaulding (1996, 1997).

COMPUTED RESULTS AND VISUALIZATION

The terrain model of the study area which covers 60 km × 60 km was generated with the DTM data and SPOT satellite image by the MultiGen II, as illustrated in Figure 2. The resolution of the DTM data and SPOT satellite image is 40 m × 40 m and 6.25 m × 6.25 m, respectively. We used the DTM as a basis to construct the computation grids, conduct the flow simulations and visualize the flow scenarios.

WQMAP was applied to predict flows under the M_2 tide forcing, upstream river inflows, and seawater intrusion. The M_2 tide is the strongest constituent in the area, accounting for 80% of the tidal energy. A constant depth of water (h = 5 m) was assumed for simulations. Simulations were performed using the grid system shown in Figure 3, with 11 layers in water depth. The grid provided reasonable resolution in the area, with grid sizes ranging from 50–250 m. The amplitude of M_2 was 1 m and assumed constant along the open boundary—the mouth of the river. Upstream inflow of Hsintien Stream, Tahan Stream and Keelung River was 200 m^3/s, 150 m^3/s and 50 m^3/s, respectively.

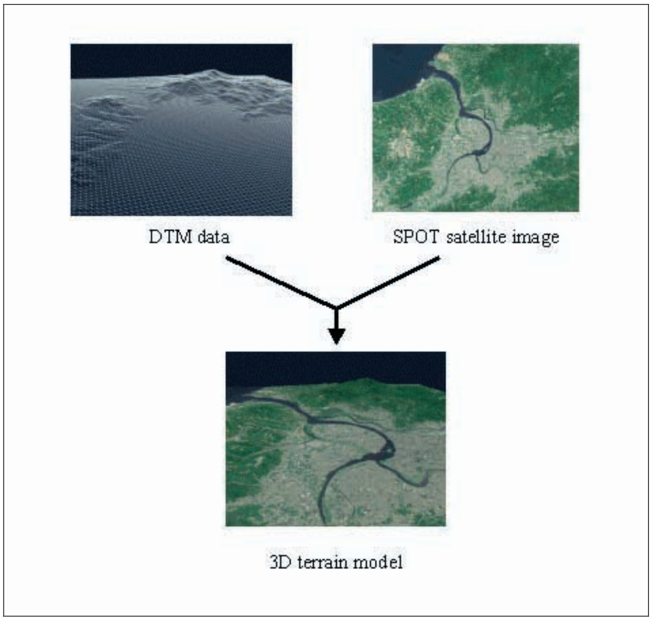

Figure 2 | Construction of the terrain model of Tamshui River Basin.

Figure 4(a) and (b) show vector plots of the predicted surface currents at ebb and flood tide, respectively. The flow pattern is principally controlled by the geometry. The flow is basically parallel to the channel. The currents are typically stronger in a constricted area and weaker in a wider channel area. The maximum predicted values of the surface M_2 tidal currents are 120 cm/s at Kuandu where Keelung River merges with Tamshui River. Flow phenomena are complicated in the neighboring area: a pair of vortices—one clockwise, the other counterclockwise—at the ebb tide, and a large clockwise vortex at maximum flood.

The salinity distribution of surface layer is presented in Figure 5(a) and (b) at ebb and flood tide, respectively.

Figure 3 | Grid configuration for Tamshui River.

To better illustrate the seawater intrusion, we use red to represent seawater (32 ppt) and blue to represent freshwater (0 ppt). The extent of seawater intrusion extends about 10 km upstream from the mouth of the river, which agrees with the simulations by Hsu *et al*. (1999) and Liu *et al*. (2000) which used a vertical (laterally averaged) two-dimensional model.

In order to easily integrate different datasets of simulations (such as velocity field and/or salinity field) with the terrain model, and migrate the visualization results onto a networked environment, the model predictions are converted into the Open Inventor format which can be easily loaded into the IRIS Performer or converted into the VRML format. This has prepared us for tele-immersion and collaboration via high-speed network (Sara *et al*. 1998; Liang *et al*. 2000). We have demonstrated some of the results on the virtual reality equipment—ImmersaDesk. Graphics libraries, such as the OpenGL, CAVE library and IRIS Performer, were used to perform real-time navigation. Figure 6 shows the integration of the terrain model, fluid flow and salinity field in the virtual environment. While wearing the three-dimensional stereo-glasses, we can use a three-dimensional wand with joystick to control the navigation, and observe the complicated flow phenomena (Liang *et al*. 1999*a*). The visualization/navigation and virtual reality program was run on a SGI Onyx2/IR graphics workstation with 2 CPUs, 1 graphics pipeline, 512 MB main memory and 64MB texture memory.

COLLABORATIVE VISUALIZATION ENVIRONMENT

Scientific visualization has proven to be very useful to explore data and present information. However, most

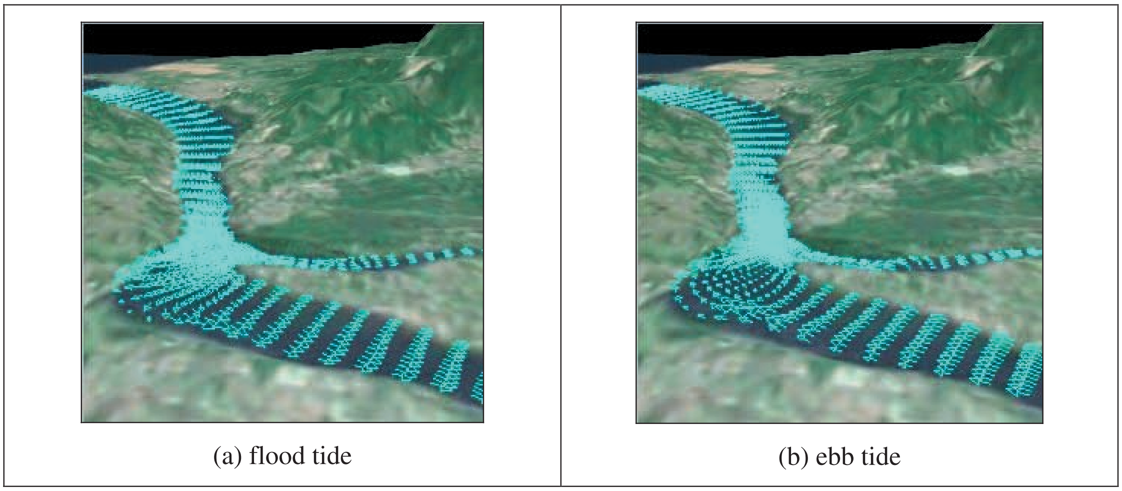

Figure 4 | Model-predicted flow currents at flood and ebb, respectively.

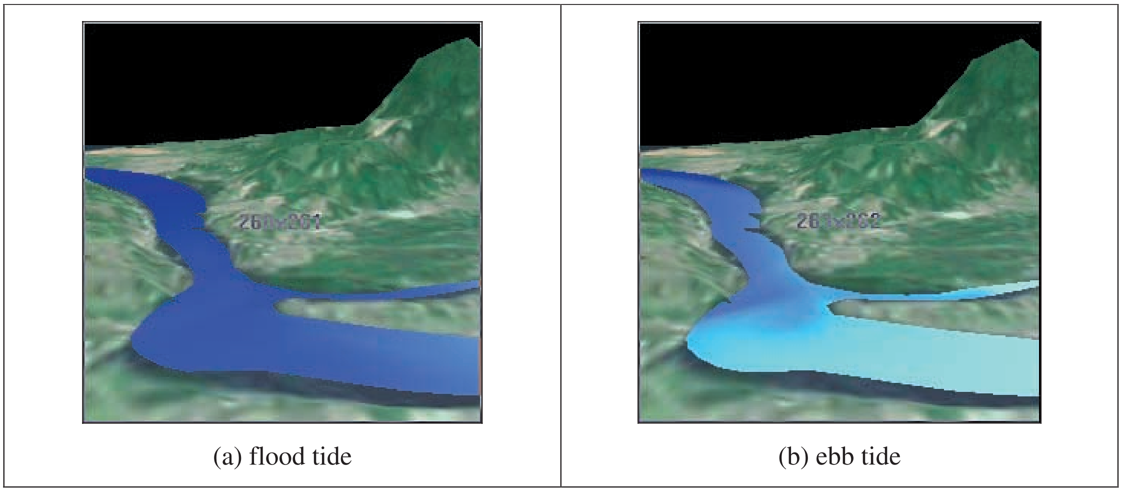

Figure 5 | Model-predicted seawater intrusion at flood and ebb, respectively.

visualization tools are standalone running on certain operating system and platform, and do not take advantage of the rapidly evolved network communications (Molkenthin & Holz, 1998). For example, the future of distributed collaboration, where ease of access to computers, databases, instruments or virtual reality devices, regardless of where they are located, gives researchers access to whatever they need. It promises to change the way people do science and engineering research worldwide. Therefore, we developed a distributed and interactive visualization environment to enhance the traditional visualization by bringing together many discipline experts so that each can contribute towards the common goal of the understanding of the object, phenomenon, data and information under investigation. We focused on the development of a collaborative visualization environment (CVE) and its application to the DTM and river flows of Tamshui River (Liang *et al*. 1999*b*, *c*, 2000). The developed system, called CVE, consists of two components: the *display* module and the *net* module, as illustrated in Figure 7. We employed OpenGL for rendering and navigating the three-dimensional terrain model as

Figure 6 | Visualization in 3D virtual digital world: integrating terrain model with computed results.

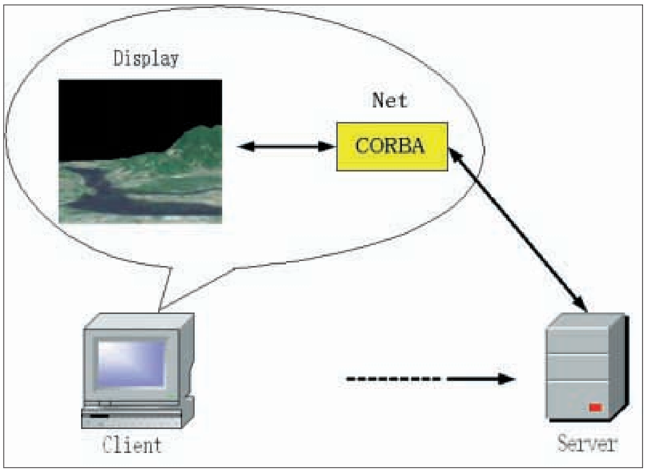

Figure 7 | Architecture of collaborative visualization environment.

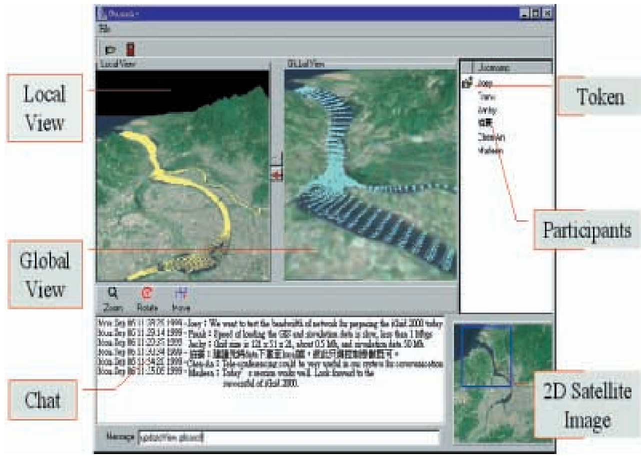

Figure 8 | Application of CVE for Tamshui River.

well as the physical behavior of a system in the *display* module, and CORBA (Common Object Request Broker Architecture) for distributed communications between the clients and server in the *net* module.

The system has been successfully applied to the visualization and navigation of the terrain model and river flows of the Tamshui River basin. Figure 8 demonstrates the interface of CVE. It enables logging in, file managing, exchanging of the token, generating 3D object from a 2D image, chatting, zooming and navigation functionalities, two views (*local* and *global*) of the current scene, and a list of the session participants. The local window shows the state of view for the local user, and the global window shows the updated state of view for all users. We can visualize, explore, gain insight, interact and collaborate with remote colleagues, and communicate our insights to others through the Internet. Such an approach has great potential for visualization and collaboration, and therefore can be widely applied to modern distributed science and engineering projects.

WWW-BASED COLLABORATION PLATFORM

The Internet as the modern information and communication technology (ICT) environment and the WWW as the flexible information system offer the possibilities for a new kind of distributed hydroinformatics information and collaboration system. Such systems support the efficient working and collaboration process among the different involved experts of distributed projects in engineering. Internet- and WWW-based software is platform independent. Computation resources (such as High Performance Computing, HPC), information bases and analysis/visualization software can be shared worldwide. A normal

PC or a low-level workstation with a WWW browser and Internet access is the only prerequisite for the application of such kinds of net-based software and information systems. In this way, the WWW software opens up new ways of collaboration in hydroscience and hydroengineering.

In parallel to the development for the distributed visualization of geometrical and physical engineering information in time and space dimensions, we are developing a WWW-based collaboration platform for the joint Taiwanese–German (TaiGer) collaboration (Molkenthin, 2001). The aim of the TaiGer project is the design, development and practical applications of such a WWW-based collaboration platform. The main idea of the project is the integration and extension of existing approaches and tools (such as VR and CVE) of both partners towards a common efficient WWW platform for the integrated analysis, visualization and documentation in coastal engineering.

The common database of these systems is a point-oriented description of the geometry, a grid-oriented description of the topology, and a description of physical state and behavior by time-dependent tensors related to the geometrical points. Based on this common principle for the description of the model data, a generalized information model for topology, geometry and physical behavior is introduced. Using the object-oriented approach of standardized classes, the information model is independent from the different simulation systems. Based on this information model and a corresponding information manager, three types of WWW tools for analysis, visualization and dynamic interactive documentation in an Internet environment are in development. These tools directly interact and integrate the 3D world of virtual reality, WWW documents and embedded software as well as GIS applications, as depicted in Figure 9. Both project partners have access to several simulation models, well proved in practical and research projects (Liang *et al.* 1999*c*; Liang & Molkenthin 1999).

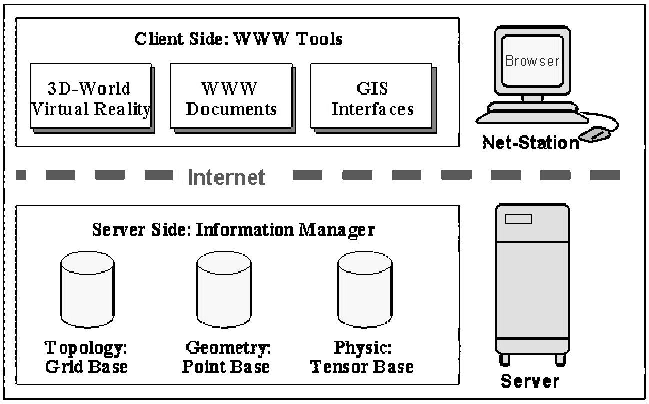

Figure 9 | Concept of WWW-based collaboration platform (TaiGer project).

CONCLUSIONS

A geographic information system (GIS) based three-dimensional hydrodynamic model system was developed and applied in Tamshui River system. The DTM data and SPOT satellite image were processed to generate the three-dimensional terrain model of Tamshui River basin. We used the DTM as the basis to construct the computational grids, and WQMAP was employed for flow simulations. The M_2 dominates the tidal currents, accounting for 80% of the total tidal energy in Tamshui River. Model predicted flow currents for the principal constituents were in good agreement with simulations by others (Hsu *et al.* 1999; Liu *et al.* 2000). Computed results were visualized in both virtual reality (VR) and collaborative visualization environment (CVE). The VR equipment–ImmersaDesk–was used to provide a semi-immersive manipulation environment, and the CAVE library and IRIS Performer were employed to perform real-time navigation. This innovative VR facility enabled us to observe local and subtle changes, and the complicated flow phenomena in the three-dimensional virtual world. The Internet-based CVE connects geographically distant computing resources and people seamlessly, efficiently and routinely over high-performance networks. It exhibits a great potential for distributed computing and databases, as well as tele-immersion for hydroengineering and hydroscience in the future.

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LIST OF ABBREVIATIONS

CORBA: Common Object Request Broker Architecture
CVE: Collaborative Visualization Environment
DTM: Digital Terrain Model
HPC: High Performance Computing
GIS: Geographic Information System
ICT: Information and Communication Technology
VR: Virtual Reality
WQMAP: Water Quality Mapping and Analysis Package
WWW: World-Wide Web

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