DECISION SUPPORT SYSTEM FOR OPTIMIZATION OF MULTI-PURPOSE RESERVOIR SYSTEM OPERATIONS: A REVIEW

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Abstract:

The multiplicity of demand for water for various purposes, viz, agriculture (irrigation and livestock), hydroelectric power, industry, domestic use, flood control and environmental concern calls for optimal utilization of available water in multipurpose reservoirs. World Commission on Dams (WCD) advocated for a more equitable distribution of the benefits to be gained from large dams and proposed the inclusion of all identified stakeholders in the planning and management of water resources stored in reservoirs. To achieve this the dam managers must take into account the water uses upstream and downstream of the dam and must also give consideration to political, organizational, social and environmental factors, not only biophysical constraints. Conventionally, the information required for this purpose has been generated by judicious audit of demand and inflow of water into the reservoirs. With the development of decision support systems (DSSs) the alternatives for judicious allocation of reservoir water for various purposes involving complicated hydrological, environmental and socio-economic constraints and conflicting management objectives became available in near-real time. Decision Support Systems (DSS) are

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computer-based tools having interactive, graphical and modelling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems. In this article we trace the history of the development of DSS for reservoir operations, provide the state-of-the-art and identify gap areas for further research.

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1.0 INTRODUCTION

The availability of quality water in adequate quantities for various purposes, namely flood control, hydropower generation, irrigation, industrial and domestic purposes is the major issue in water management. In this context, optimization of reservoir operations assumes greater significance. It involves determination of the optimal release volumes in the successive time periods so that the expected total rewards resulting from the operations are maximized. Furthermore, the deregulation of the power industry emphasizes the need for maximizing hydropower benefits. Reservoir managers must improve the management of existing resources and must adapt quickly to changing objectives and requirements. Despite several decades of intensive research on the application of optimization models to reservoir systems, a continuing gap between theoretical developments and real-world implementations has been noted (Yeh, 985; and Wurbs,1993). The disparity may be attributed, amongst other factors, to scepticism of most of reservoir system operators in adopting optimization models which are mathematically more complex than the existing simulation models, to replace their judgment, lack of the scope for incorporating the risk and uncertainty in optimization models, and wide range and varieties of optimization methods making the decision by the operators of the reservoir system very complex. Many of these hindrances to optimization in reservoir system management are being overcome through ascendancy of the concept of decision support systems and dramatic advances in the power and affordability of desktop computing hardware and software.

2.0 BACKGROUND

Decision support system (DSS) is primarily concerned with supporting decision-making in terms of problem identification and problem solving at all decision-making levels. A DSS provides support to the user and does not replace the individual. The emphasis is on the enhancement of a decision-making process by allowing use of quantitative models that are appropriate to the problem. The term system includes both, the user and the machine. The machine is a computer that, for now, operates in interactive mode through an input/output terminal. System also implies availability of quantitative models and some type of database. In the framework of this definition, these elements are more providing service to the decision maker than directly delivering a decision. Integrating all previous comments and characteristics, the decision support system can be defined as "an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems." (Sprague and Carlson, 1982). Key terms in this definition are: *interactive, data,* and *models*, which are a recurring theme among developers of water management DSSs. In the context of water resources management a DSS can be defined as "an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured water resource management problems (McKinney,2004).

A Decision Support System allows decision-makers to combine personal judgment with computer output, in a user-machine interface, to produce meaningful information for support in a decision-making process. Such systems are capable of assisting in solution of all problems (structured, semi-structured and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision-maker's approach to problem identification and solution (modified after Parker and Al-Utabi, 1986; Thierauf, 1988; and Simonovic and Savic, 1989)..(DSS_Flood12-02-17). In the context of optimization of reservoir operations, decision makers are the planners and managers. The objective of these decision makers is, among others, to provide the reliable supply of water with a quality appropriate for its use, production of hydropower, protection from floods, and protection of ecosystems. Three main subsystems must be integrated in an interactive manner in a DSS (Orlob, 1992; Close et al., 2003): (1) a user-interface for dialog generation and managing the interface between the user and the system; (2) a model management subsystem; and (3) an information management subsystem. Considering this in more detail, DSS architecture consists of (i) Data collection, (ii) Data processing ,(iii) Analysis, (iv) Decision support, and (v) Decision implementation (Fig.-1).

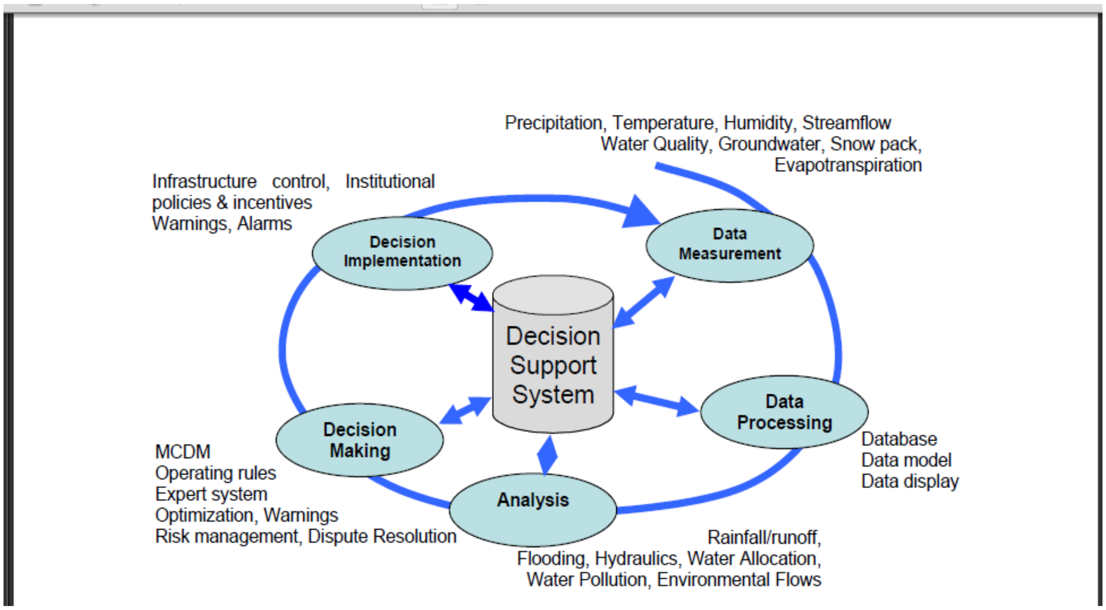

Fig.-1Schematic of a general framework for a water resources DSS (Adapted from McKinney,2004).

2.1 Water Management Decisions

Although there are several areas of decision making in water resources management the focus is given here on two principal areas, namely (i) *Emergency water management* - involving floods or chemical spills; and (ii) *Water regulation and allocation* - involving water supply for municipalities, agriculture, industry, hydropower production, and environmental protection. Decision making regimes tend to be different for these two areas due to the difference in time available for making decisions- hours in former case and days to months in the latter.

2.1.1 Emergency Water Management

Early Warning Systems - Early warning systems for floods or accidental chemical spills are information systems designed to send automated hydrologic and water quality data regarding water-related disasters to river basin planners, who combine them with meteorological data and river basin models to disseminate hazard forecasts and formulate strategies to mitigate economic damage and loss of human life. Early warning systems are typically comprised of early warning subsystem, risk information subsystem, preparedness subsystem; and communication subsystem. *Accidental Chemical Spills*

Accidental chemical spills are a major concern for areas that have vulnerable riverine ecosystems and cities with vulnerable drinking-water supplies and weak spill response capabilities. In order to provide emergency response capability to protect against accidental spills, studies are performed to determine travel times in river reaches. The results of these studies can be used to plan emergency responses to chemical spills into rivers, including guiding decisions regarding closing and reopening of intakes to drinking-water systems. A system for supporting response to accidental spills should include a database of potential spill sites and locations of agricultural chemicals, oil tanks, pesticides, and hazardous wastes stored on or near a river. The database should also include the bridges and rail lines which cross rivers and often serve as transport for hazardous materials. From the use of such a DSS tool, spill responders can quickly find directions to spill sites, emergency contacts and details about chemicals and how they react with the river under various conditions. Spill responders can also run simulation models of spills to practice their response and determine how long it takes for a spill to reach critical locations downstream.

2.1.2 Water Regulation and Allocation

2.1.2.1Reservoir and Lake Management

In the area of reservoir and lake management, support is needed to make decisions regarding water supply for agriculture, industries and domestic purposes, and hydropower operation, pollution control, mitigation of climate change effects, reservoir eutrophication, phosphorus control strategies, and operation of multiple reservoir systems. Different types of models are required to provide support in this area, such as, water allocation models to determine the distribution of water for economic production and environmental protection in a basin; or two- and three- dimensional models to analyze water quality in lakes.

2.1.2.2 Non-Point Source Pollution

In the context of non-point source pollution decision support is needed to make plans for agricultural chemical use or protection of vulnerable water bodies, stream and aquifers. Modeling and managing agricultural non-point source pollution typically requires the use of a distributed parameter watershed model. The data management and visualization capabilities are needed to allowed decision makers to identify and analyze problem areas easily. **2.1.2.3 Conjunctive Use of Surface and Groundwater**

Since decision makers are typically required to consider a multitude of social, legal, economic, and ecological factors, DSSs have great potential for improving the planning and management of conjunctive use systems. This may require the integration of a number of simulation and optimization models with graphic user interface capabilities to provide an adequate framework for the discussion of water allocation conflicts in a river basin. Conjunctive use models and multi-objective decision methods can be combined to provide decision support for inter-basin water transfer planning allowing decision makers to analyze the social, economic, and environmental impacts of water transfers. **2.1.2.4 Water Treatment and Distribution Systems**

The design and operation of water treatment and distribution systems are also complex tasks in which the experience of the designer or operator is critical. Typically, models of these systems have sacrificed physical accuracy so that solutions could be obtained in a timely manner. User evaluation of trade-offs between model solvability and accuracy in the design of water supply and distribution systems, evaluate investment options, and demonstrate interaction between water quantity and quality. General network simulation and optimization models can be used in scheduling and control methodology for water distribution systems in urban distribution systems to determine proper structural changes to the system that minimize disruption to existing customers. Recently, evolutionary methods, such as genetic algorithms, have been used to solve realistic models of large urban water distribution systems which are intractable with more traditional methods.

3.0 AVAILABLE WATER MANAGEMENT DECISION SUPPORT SYSTEMS The following decision support systems are generally available either at no cost or for a license fee: **3.1 Emergency Water Management DSSs**

3.1.1 Flood Management Decision Support Systems

*CWMS :*The Corps Water Management System” (CWMS) is an automated water management information system(Fritz, J.A., et al., 2002) and is comprised of an integrated system of hardware and software that begins with the receipt of hydromet, watershed, and infrastructure data which are used to determine the hydrologic response of a watershed, including reservoir inflows and local uncontrolled downstream flows. Reservoir inflows are processed to compute releases to meet reservoir and downstream operation goals. River profiles are computed, inundated areas mapped, and flood impacts analyzed. Various future precipitation scenarios can be considered, hydrologic response altered, reservoir release rules investigated, and alternative infrastructure conditions evaluated. CWMS uses a relational database (ORACLE) and the models incorporated in the system include EC-HMS (hydrologic modeling), HEC-RAS (river analysis), HEC-ResSim (reservoir evaluation) and HEC-FIA (flow impact analysis).

SMS: The Surface Water Modeling System (SMS) is an interface providing access to one-, two-, and three-dimensional hydrodynamic modeling software, including pre- and postprocessor software for surface water modeling (EMRL, 2004). SMS models allow calculation of water surface elevations and flow velocities for shallow water flow problems, for both steady-state or dynamic conditions. Additional applications include the modeling of contaminant migration, salinity intrusion, and sediment transport (scour and deposition).

WMS (EMRL, 2004) - Similar to SMS and GMS, the Watershed Modeling System (WMS) has been developed by the Environmental Modeling Research Laboratory (EMRL) at **Brigham** Young University. WMS is a graphical modeling environment for watershed hydrology and hydraulics. WMS also includes tools for automatically delineating watersheds and sub-basins including a direct linkage with ArcGIS. WMS license fees are $4,600 for a single user including all modules and interfaces.

3.1.2 Accidental Spill Decision Support Systems

DBAM: The "Danube Basin Alarm Model" (DBAM) is an operational model for the DAWEPS for simulating the travel time and expected peak concentrations of substances released during accidental spills (Gils and Groot, 2002; Gils et al, 2004). The DBAM was designed to provide a fast assessment of the effects of a spill using limited and readily available data. The Rhine Alarm Model (RAM) was used as the basis for DB AM, but DBAM goes one step further calculates the spreading of pollution across the river (Greencross, 2003). The DBAM software consists of three main parts:

• A user interface program that reads network data and allows the user to perform selections and input data on accidental spills, and run simulations.

• A model program that reads the system input data defining the river and the case dependent input files defining the spill and associated hydrology. It produces output files containing simulation results at selected locations and times; and

• A result display program that reads the simulation result files together with river network data and produces graphics and tables.

RiverSpill: RiverSpill is a GIS (ArcView 3.2) based system that models the real-time transport of constituents within a river system (Samuels et al., 2003; SAIC, 2003). RiverSpill calculates time of travel and concentration based on real time stream flow measurements, decay, and dispersion of constituents introduced into surface waters. RiverSpill contains the following capabilities: Release Type - Instantaneous or Continuous release; Agent Type - Chemical or Biological Agents; and Solution Type - Peak or non-Peak concentration. By selecting a location on a river to introduce a chemical or biological constituent, the model performs the following functions: Tracks the contaminant constituent under real time flow conditions to a water supply intake; determines the concentration of contaminant as it decays and disperses in the river; associates an intake to a water treatment plant; and identifies the population served by the plant. Instantaneous and complete mixing of the pollutant in the river water column is the most important assumption in River Spill. Any deviation from these conditions requires detailed analysis of physical and chemical processes.

WQModel: In WQModel, mass is passed to downstream locations in a basin and decays according to travel time and decay coefficients (Whiteaker and Goodall (2003) and Whiteaker (2004). The decay rate represents the loss of mass due to biological decay, sorption, uptake, etc, as material moves downstream. Accumulation of mass in lakes and other water bodies can also be calculated assuming the lake has constant inflow equal to its outflow, and that mass entering the lake is instantaneous and perfectly mixed within the lake.

3.2 Water Allocation Decision Support Systems

Aquarius: AQUARIUS is a temporal and spatial allocation model for managing water among competing uses (Diaz et al., 1997). The model is driven by economic efficiency which requires the reallocation of all flows until the net marginal return of all water uses is equal. The model is implemented in C++ under an object oriented programming framework, where each system component (e.g., reservoir, demand area, diversion point, river reach) is an object in the programming environment. In the GUI, the components are represented by icons, which can be dragged and dropped from the menu creating instances of the objects on the screen. These can be positioned anywhere on the screen or removed. Once components are placed on the screen, they are linked by river reaches and conveyance structures. The model performs optimization to identify tradeoffs between water uses by examining the feasibility of relalocating water to alternative uses. Each water use is represented by an exponential demand curve (i.e., a marginal benefit function). The model is formulated as a quadratic programming model with a linear constraint set.

Aquatool: Aquatool consists of a series of modules integrated in a system in which a control unit allows the graphical definition of a system scheme, database control, utilization of modules and graphical analysis of results(Andreu, et al., 1991; Andreu, et al., 2003; Andreu, 2004). Modules include: surface and ground water flow simulation; single- and multi-objective optimization of water resources; hydrologic time series analysis; risk based WRS management. Water quality is not included. All documentation is in Spanish.

CALSIM: The CALifornia Water Resources SImulation Model (CALSIM) was developed by the California State Department of Water Resources (DWR) and the United States Bureau of Reclamation for planning and management of the California State Water Project and the U.S. Central Valley Project (DWR, 2004). CALSIM is a hybrid linear optimization model which translates the unimpaired (i.e. natural) stream-flows into impaired streamflows, taking into account reservoir operating rules and contract water demands exerted at model nodes (Quinn et al., 2004). CALSIM uses a mixed-integer linear programming solver to route water through the river network at each time step. The model code is written in Water Resources Engineering Simulation Language (WRESL), a high-level programming language developed by the DWR, and the system of WRESL equations is solved using a proprietary solver XA (Sunset Software Inc.). The model is used to simulate existing and potential water allocation and reservoir operating policies and constraints that balance water use among competing interests (Quinn et al., 2004). Policies and priorities are implemented through the use of user-defined weights applied to the flows in the system. Simulation cycles at different temporal scales allow the successive implementation of constraints. The model can simulate the operation of relatively complex environmental requirements and various state and federal regulations.

DELFT-TOOLS **:**Delft-Tools is a framework for decision support developed by Delft Hydraulics for the integrating water resources simulation programs. Functions of the system include scenario management, data entry, and interactive network design from map data, object-oriented database set-up, presentation, analysis and animation of results on maps (Delft Hydraulics, 2004) . DELFT-TOOLS integrates the Delft Hydraulics models: SOBEK, RIBASIM and HYMOS. SOBEK is a one-dimensional river simulation model that can be used for flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, ground-water level control, river morphology, salt water intrusion and surface water quality. RIBASIM (River Basin Simulation Model) is a river basin simulation model for linking water inputs to water-uses in a basin. It can be used to model infrastructure design and operation and demand management in terms of water quantity and water quality. HYMOS is a time series information management system linked to the Delft Hydraulics models.

*EPIC***:** Originally developed by the USAID project "Environmental Policies and Institutions for Central Asia") EPIC determines optimal water allocation in a river basin by multi-objective optimization in monthly time steps. Transport of conservative substances, e.g., salt, and management of generated hydroelectricity can also be optimized with the model. Water management alternatives can be developed for a time period of up to 15 years based on varying supplies and changing requirements of the water users.Models created in EPIC perform optimization calculations for operation of river networks according to a ranked list of objectives. EPIC provides an interface for automatic network and model creation, as well as data input, input of constraints on reservoirs, channel flow and salinity, setting of the objective weights and visualization of results. The modeling system generates nonlinear optimization model files for solution by the General Algebraic Modeling System - GAMS (Brooke et al., 1998). The main optimization criterion of EPIC is to minimize deficits of water delivery to users; other criteria include satisfying environmental flows, and maximizing reservoir over year storage (McKinney and Savitsky, 2001). Policy decisions are modeled through changes in the weights on the various objective terms. A detailed description of the EPIC modeling system for river, salt, and energy management and its application to the Aral Sea basin can be found in McKinney and Kenshimov (2000) and McKinney and Savitsky (2001).

Mike-Basin: It couples ArcView GIS with hydrologic modeling to address water availability, water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints in a river basin (DHI, 2004). MIKE-BASIN uses a quasisteady- state mass balance model with a network representation for hydrologic simulations and routing river flows in which the network arcs represent stream sections and nodes represent confluences, diversions, reservoirs, or water users. ArcView is used to display and edit network elements. Water quality simulation assuming advective transport and decay can be modeled. Groundwater aquifers can be represented as linear reservoirs. Current developments are underway to utilize the functionality of ArcGIS-9 in MIKE-BASIN. Basic input to MIKE-BASIN consists of time series data of catchment run-off for each tributary, reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to water demands and rights (for irrigation, municipal and industrial water supply, and hydropower generation), and information describing return flows.

*ModSim:*ModSim is a generalized river basin DSS and network flow model with capability of incorporating physical, hydrological, and institutional/administrative aspects of river basin management, including water rights(Labadie et al., 2000; Shannon, et al., 2000 ; Dai and Labadie, 2001; Labadie, 2004). ModSim is structured as a DSS, with a graphical user interface (GUI) allowing users to create a river basin modeling networks by clicking on icons and placing system objects in a desired configuration on the display. Through the GUI, the user represents components of a water resources system as a capacitated flow network of nodes (diversions points, reservoirs, points of inflow/outflow, demand locations, stream gages, etc.) and arcs (canals, pipelines, and natural river reaches).

*OASIS:*Developed by Hydrologics, Inc. Operational Analysis and Simulation of Integrated Systems (OASIS) is a general purpose water simulation model (Hydrologics, 2001; Randall et al, 1997). Simulation is accomplished by solving a linear optimization model subject to a set of goals and constraints for every time step within a planning period. OASIS uses an object-oriented graphical user interface to set up a model, similar to ModSim. A river basin is defined as a network of nodes and arcs using an object-oriented graphical user interface. Oasis uses Microsoft Access for static data storage, and HEC-DSS for time series data. The Operational Control Language (OCL) within the OASIS model allows the user to create rules that are used in the optimization and allows the exchange of data between OASIS and external modules while OASIS is running.

*RiverWare:*RiverWare is a reservoir and river system operation and planning model(Carron et al., 2000; CADWES, 2004). The software system is comprised of an object-oriented set of modeling algorithms, numerical solvers and language components. Site specific models can be created in RiverWare using a graphical user interface (GUI) by selecting reservoir, reach confluence and other objects. Data for each object is either imported from files or input by the user. RiverWare is capable of modeling short-term (hourly to daily) operations and scheduling, mid-term (weekly) operations and planning, and long-term (monthly) policy and planning. Three different solution methods are available in the model: simulation (the model solves a fully specified problem); rule-based simulation (the model is driven by rules entered by the user into a rule processor); and optimization (the model uses Linear Goal- Programming Optimization).

*URGWOM:*Developed by the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, U.S. Bureau of Indian Affairs, the International Boundary and Water Commission (U.S. Section), and the U.S. Army Corps of Engineers (USACE, 2004b) the Upper Rio Grande Water Operations Model (URGWOM) is used to support studies related to water accounting and annual operating plans for the Rio Grande from the Colorado/New Mexico border to El Paso, Texas. The model is capable of simulating water storage and delivery operations and for flood control modeling. URGWOM is a basic "backbone" water operations DSS meant to replace the current, more cumbersome, methods that are used to plan, analyze, and evaluate river and reservoir management options. URGWOM uses HEC-DSS as the primary database.

*CRSS***:** The Colorado River Simulation System (CRSS) model (Schuster, 1987) was created in the early 1980s to model the Colorado River Basin in order to schedule, forecast and plan reservoir operations. Since CRSS was created to model the Colorado River Basin, many of the characteristics of the basin were hard-coded into the model, including the topography of the basin itself, the methods for calculating evaporation, bank storage and other reservoir-specific information, and the policies by which water is allocated (Wehrend, 2002). As new information about the basin and the operation policies and technology became available, CRSS had to be updated and RiverWare was chosen for this task.

*WaterWare:*WaterWare is a decision support system based on linked simulation models that utilize data from an embedded GIS, monitoring data including real-time data acquisition, and an expert system (Fedra, 2002; Jamison and Fedra, 1996). The system uses a multimedia user interface with Internet access, a hybrid GIS with hierarchical map layers, object databases, time series analysis, reporting functions, an embedded expert system for estimation, classification and impact assessment tasks, and a hypermedia help- and explain system. The system integrates the inputs and outputs for a rainfall-runoff model, an irrigation water demand estimation model, a water resources allocation model, a water quality model, and groundwater flows and pollution model.

6.0 Conclusion

Highly conflicting and competing demands for finite water resources call for instant availability of viable alternatives for optimization of operations for planners and decision makers of reservoirs. This is especially true is some of the operations like flood control or accidental chemical release into the reservoirs. Traditional approaches to optimization have not been very effective in providing desired solutions. The development of computer technology and attendant developments in softwares addressing decision making has ushered in a new era in optimization of reservoir operations. There has been proliferation decision support systems for reservoir operations for various purposes including flood control, timely and most appropriate action in the event of accidental chemical release into the reservoir, meeting the demands for water for irrigation, hydropower, industries, domestic, etc. The DSSs provide several alternatives for a particular operation to planners and decision makers. Although opportunities for real-world applications are enormous, actual implementations remain limited or have not been sustained. The traces the history of decision support systems (DSSs) for optimization of reservoir operations, and provides an overview of the development therein *vis-a-vis* developments and advancements in software, hardware and data integration technology. Being a complex phenomenon there exists no single DSS for various components of reservoir operations. We conclude the article by admitting that the development of DSS for optimization of reservoir is a continuous and evolving process leading to newer and more user friendly systems.

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