RAINFALL-RUNOFF MODEL FOR BLACK CREEK WATERSHED, NAVAJO NATION

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ABSTRACT

This paper develops a rainfall-runoff model for estimating surface and peak flow rates from precipitation storm events on the Black Creek watershed in the Navajo Nation. The Black Creek watershed lies in the southern part of the Navajo Nation between the Defiance Plateau on the west and the Chuska Mountains on the east. The area is in the semiarid part of the Colorado Plateau on which there is about 10 inches of precipitation a year. We have two main purposes for embarking on the study. One is to determine the amount of runoff and peak flow rate generated from rainfall storm events falling on the 655 square mile watershed and the second is to provide the Navajo Nation with a method for estimating water yield and peak flow in the absence of adequate data. Two models, Watershed Modeling System (WMS) and the Hydrologic Engineering Center (HEC) Hydrological Modeling System (HMS) that have Geographic Information System (GIS) capabilities are used to generate stream hydrographs. The latter show peak flow rates and total amounts of stream flows produced from rainfall storm events. Two 24-hour rainfall amounts, 1.1 inches and 0.6 inches, are imputed into the WMS and HEC HMS modeling system and evaluated to produce 1770 cfs and 3.9 cfs of peak flows and 1106.5 acre feet and 2.7 acre feet of total flow volumes, respectively. Even though the first one seems to be a little high compared to historical peak flows from the watershed, the outcomes seem to be quite appropriate for the study area when compared with gauging site flows at other times as well as with flows from well-instrumented nearby watersheds.

INTRODUCTION

One of the two primary objectives of this research project was to develop an event-based precipitation-runoff model for estimating surface flow and peak flow rate from a particular watershed. To accomplish this, we developed a prototype watershed model using the Black Creek watershed as a case study. We selected the Black Creek watershed, because it has a large area that encompasses the most populated part of the Navajo Nation, where the towns of Fort Defiance and Window Rock are located. It is also located between the two most prominent mountain ranges in the area, the Defiance Plateau in the west and the Chuska Mountains in the east (see Figure 1). Because this area is located in the semi-arid part of the Colorado Plateau it receives about 10 inches of precipitation a year.

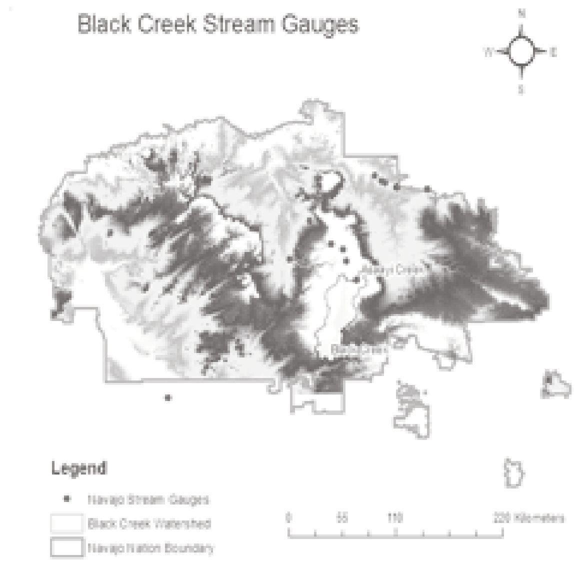

Figure 1. Physiographic map of the Navajo Nation with the Chuska Mountain and Defiance Plateau and Stream Gaging Stations.

The main purpose for the modeling effort in this study was to produce a reliable watershed model in the presence of inadequate data. Specifically, the model used the 655 square mile Black Creek Watershed as a case study to determine the amounts of surface runoff and peak flow rates from precipitation storm events that fell in the watershed. The developed approach is expected to be transportable to other watersheds throughout the Navajo Nation.

Watershed Physical Characteristics

The largest Native America tribal community, the Navajo Nation encompasses approximately 27,000 square miles straddling the states of Arizona, New Mexico, and

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Utah in the Four Corners region of the southwestern United States. The area is characterized by a semi-arid environment with Great Basin grassland and shrub vegetation types except on the high altitude mountain slopes which are characterized by Ponderosa Pine and mixed conifer forests (Wright et al., 1973). Precipitation events in this region occasionally produce damaging flash floods. Hence, there is a need for estimating peak flow rates from storm events falling on watersheds to develop a good floodplain management plan and reliable information to promote proper use and management of floodplains, to protect property and lives and to work on other development plans (NNDWR, 2002).

The Black Creek watershed is relatively a large landscape that covers an area of 655 square miles (or 419,200 acres). It is located in the Upper Puerco River Basin, a tributary of the Little Colorado River. The watershed stretches from the confluence of the Black Creek with the Puerco River in the south onto the western flanks of the Chuska Mountains on the east and the eastern slopes of the Defiance Plateau on the west (see Figure 1). Although the narrow Black Creek Valley separates the Chuskas from the Defiance Plateau, they are two halves of the same monocline (upward) in the Earth's crust that geologists call the "Defiance Uplift" (U.S. Army Corps of Engineers, 2004). There, "piggybacked" upon the larger Colorado Plateau, the Defiance Uplift has been raised up to about 8,000 feet above sea level and worn down repeatedly for hundreds of millions of years. The more rugged Chuskas reach up to nearly 10,000 feet elevation. In either case, some of the rain and snow that fall on the mountains drain southward into the upper Puerco River found near the southern boundary of the watershed. The northern part of the Black Creek watershed is the location of the towns of Window Rock and Fort Defiance, the seats of Navajo Nation governmental departments. The mouth of the watershed, at 35 degrees 20' 00" latitude and 109 degrees 12'13" longitude, is the location of the Black Creek stream gaging station. The station was established in 1986 (Irving, 2006). At that point, the elevation of the watershed is 6,110 feet while its highest point on the Chuska Mountains reaches 9,120 feet above sea level.

Motivation for the Study

The motivation for engaging in the study leading to this paper was the Navajo Nation hydroclimate data and needs assessment study of Garfin et al. (2007). That study indicated that there were many important issues related to hydroclimate instrumentation and surface water flow estimation that need to be rectified in the Navajo Nation. Most watersheds in the Navajo Nation do not have any stream gaging facilities, and where gages exist they are not reliable and the data obtained are inadequate and, in many cases, not in useable form. The reasons behind the latter conditions are (1) absence of high quality data, (2) lack of proper data collection, handling, storage and processing methods, and (3) shortage of quality control and quality assurance in operating the stream gaging stations. Hence, any stream flow measurement and estimation from the Black Creek watershed in the Navajo Nation faces these challenges.

In spite of these challenges, however, the Navajo Department of Water Resources (NDWR) is doing a very good job in providing some basic water resources information to the public. The study in this paper is a part of the efforts that have been made by the NDWR to improve hydroclimate data collection, transport, storage, and processing to better satisfy the needs of the Navajo Nation (Tecle et al. 2009). But, where there are no reliable stream gages and no adequate stream flow data, a cost-effective method of estimating surface flow of both water yield and peak flow rate types is through a rainfall-runoff modeling scheme. One method, we found to be appropriate and reliable for determining surface flow and peak flow rate in the study area, was the use of the WMS and HEC HMS models in Aquaveo (Tecle et al., 2009). The method is described in some detail below.

METHODS

Stream flow determination from ungagged watersheds requires many pieces of information related to climate, soil moisture, land cover, land use management, and soil physical characteristics. Many of these pieces of information have temporal and spatial characteristics that require integration using different modeling schemes. The modeling effort done in this study consisted of delineating the study watershed and obtaining the necessary biophysical and climate data from various sources. We developed a GIS map that integrated the spatial distributions of soil types, parent material, vegetation cover, land use, drainage area, topography, precipitation, and other watershed characteristics. The spatial distributions of these characteristics and other data from the watershed were entered into off-the-shelf models known as the Watershed Modeling System (WMS) and the Hydrologic Engineering Center (HEC) Hydrological Modeling System (HMS) contained in Aquaveo (Aquaveo, Water Modeling System, 2009). The GIS software part of Aquaveo integrated the overlays of the different climate and biophysical watershed

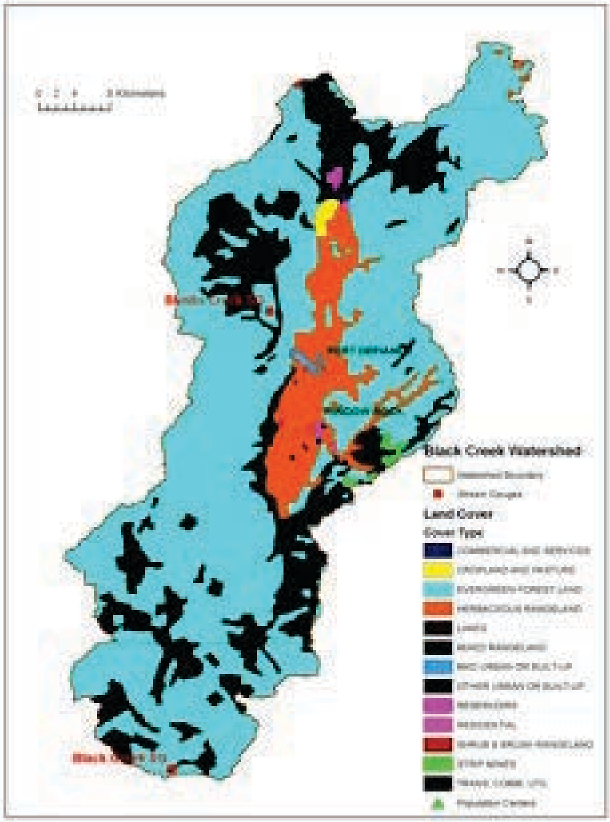

Figure 2. Vegetation cover distribution in Black Creek Watershed developed from EPA STATSGO database.

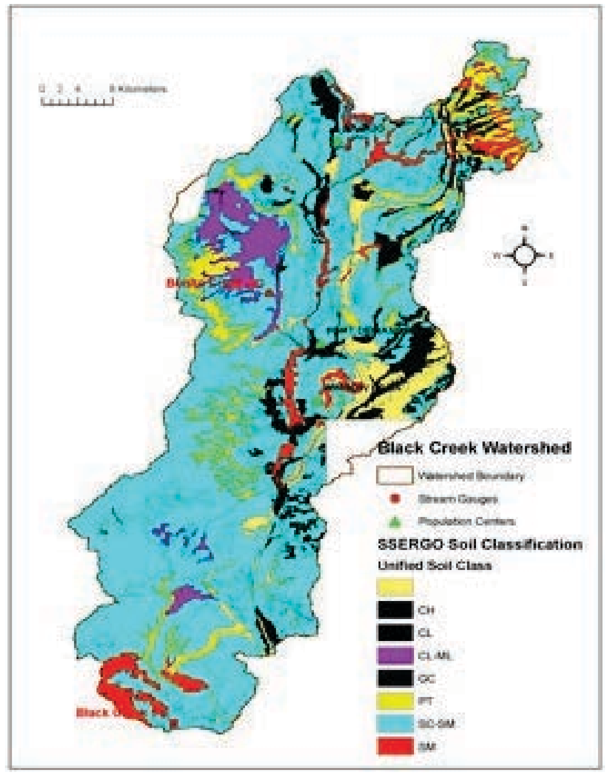

Figure 3. Unified soil classification in Black Creek watershed developed from NRCS SSERGO database (CH = clay of high plasticity, CL = clay, CL-ML = clay-silt, GC = clayey gravel, PT = peat, SC-SM = clayey sand - silty sand SM = silty sand).

characteristics and compartmentalized the watershed into relatively homogenous sub-watersheds in which specific curve numbers and area values were determined.

Integrating Watershed characteristics using GIS

The specific spatial software used to create the GIS maps was ESRI's ArcGIS 9.3. All the maps used as overlays were plotted in the same extent and scaled by clipping pieces of spatial information to a Black Creek watershed boundary and then re-projected to NAD83 UTM 12N when necessary. Each map was constructed to represent a single major attribute such as monthly average precipitation, monthly average temperature, land cover, elevation, slope, aspect, main soil characteristics and land use activities. Many of these datasets came from the USDA Geospatial Data Gateway at http://datagateway.nrcs.usda.gov/GatewayHome.html. Others such as the soil data are obtained from one of two sources. 1) The Soil Survey Geographic Database (SSURGO) available from the Natural Resources Conservation Service (NRCS) Soil Data Mart website at: http://soils.usda.gov/survey/geography/ssurgo/ and http://soildatamart.nrcs.usda.gov/, and 2) STATSGO Soils Data and EPA Vegetation Data available from the U.S. Environmental Protection Agency (EPA) website at http://www.epa.gov/waterscience/ftp/basins/gis_data/huc. One advantage of the EPA's database was that land use and soil type data were retrieved together using one download. Geographic boundaries and point locations were then included to help users orient the map. Figures 2 and 3 are presented to serve as examples of the mapping process and the types of maps produced and used in the study. The two maps consist of Black_Creek_Land cover from EPA STATSGO database (Figure 2), and the Black_Creek SSERGO unified soil classification data from NRCS (Figure 3). The pieces of information from these databases along with others such as soil parent material, topography, springs and streams, etc., were used as map overlays and integrated using the ESRI's ArcGIS 9.3 software (http://www.esri.com/software/ arcgis/) to determine sub watersheds with specific area and curve number values.

Table 1. Reference NRCS Curve Number Values for Some Common Land Uses and the Four Hydrologic Soil Groups

Code	Land Use Description	Hydrologic Soil Group			
		A	B	C	D
11	Residential	57	72	81	86
12	Commercial and Services	89	92	94	95
14	Transportation, Communications, and Utilities	83	89	92	93
16	Mixed Urban or Built-up Land	81	88	91	93
17	Other Urban or Built-up Land	63	77	85	88
21	Cropland and Pasture	49	69	79	84
31	Herbaceous Rangeland,	49	69	79	84
32	Shrub and Brush Rangeland,	35	56	70	77
33	Mixed Rangeland	35	56	70	77
42	Evergreen Forest Land	36	60	73	79
75	Strip Mines, Quarries, and Gravel Pits	77	86	91	94

Table 2. GIS_ArCInfo generated homogenous sub-watersheds and their specific areas and curve number values

WS No.	Watershed Area	Curve # value	WS No.	Watershed Area	Curve # value .
1	4258.23	70.0	24	4922.22	66.1
2	5564.57	67.0	25	6560.56	67.9
3	5670.00	67.3	26	4265.44	70.4
4	8384.81	70.2	27	7708.11	66.3
5	8971.15	70.1	28	8444.28	70.6
6	44.38.66	75.8	29	8400.98	73.9
7	3442.67	70.6	30	5571.78	76.5
8	17841.25	67.7	31	9144.56	75.4
9	7289.51	74.6	32	10190.88	77.7
10	17574.21	75.7	33	6943.08	77.3
11	7520.46	78.7	34	12096.25	79.0
12	6365.69	77.6	35	33206.95	76.0
13	27166.05	76.1	36	6789.00	74.0
14	4453.10	78.7	37	9555.75	73.8
15	8509.21	73.0	38	13092.00	76.3
16	8156.39	75.5	39	8646.37	75.6
17	11930.26	71.0	40	3963.50	74.0
18	8532.79	69.0	41	8980.14	75.6
19	5615.09	64.0	42	8956.71	72.6
20	10097.05	74.3	43	3572.58	76.1
21	18209.34	68.3	44	9620.71	70.6
22	5651.17	77.3	45	6986.38	64.2
23	4063.36	68.2			

Delineating sub-watersheds using WMS

WMS 8.1 software was used to create sub-watersheds. We used digital land use and soil characteristic shape files to create using WMS the NRCS curve number values automatically. The process consists of determining spatial distribution of land use and land cover characteristics by activating Land Use shape files to produce a land use layer (Aquaveo, Water Modeling Solutions, 2009). The same process was repeated to create Soil Type Cover. Integration of the latter with a drainage module produced the Hydrologic Soil Groups for the different parts of the watershed. Then, by integrating the digital land use and the Hydrologic Soil Groups (A, B, C, D), the NRCS curve number values were generated automatically using WMS. General curve number values for various land uses and Soil Hydrologic Groups used as reference values are shown in Table 1. More information on developing curve number values is available from the website http://emrl.byu.edu/gsda. The outcome of this WMS process was a compartmentalized Black Creek watershed, divided into many relatively homogenous sub-watersheds the areas and curve number values of which are presented in Table 2. Once the watershed map

Figure 4. Location of stream and rainfall gages (most of them non-recording) in the Black Creek Watershed.

is divided into sub-watersheds, then one outlet from each sub-watershed is determined to empty the outflows from the sub-watershed to the next one below it in a cascading fashion (Hans et al., 1982; Tecle et al., 2009).

Developing spatially distributed Precipitation event

Even though the study area has many rain gages (see Figure 4), most of them were non-recording gages (see the labeled dots in the figure) from which monthly data were collected. Even though precipitation data were generally available in monthly totals we developed and used a precipitation-elevation relationship to extrapolate event data from one sub-watershed to all the other sub-watersheds on the study site. The equation below was developed to extrapolate daily rainfall from the monthly average values. It was based on general north central Arizona elevation – precipitation relationships. NOAA daily precipitation maps obtained from http://www.cpc. noaa.gov/products/precip/realtime/ were used to determine existence and approximate amount of rainfall in each sub-watershed during the extrapolation process; when a map shows absence of rainfall in a sub-watershed a zero value was then assigned to that watershed.

$$Dn = \left[\frac{En}{E_{BET}} \right] R_{BET}$$

Where Dn = Daily rainfall on station n
En = Elevation of station n
EBEN = Elevation of Bonito recording raingage location site
RBEN = Daily rainfall from the raingage at Bonito gaging site

The above equation is multiplied by a rainfall distribution factor, Rf the value of which ranges from 0 to 3 depending on the amount of rainfall that fell on any sub-watershed n relative to the amount that fell in the sub-watershed where the Bonito Creek (BEN) gage is located. The relative value was determined from the National Weather Service precipitation map for the same period. When a particular sub-watershed in a map shows no rainfall, the Rf value for that sub-watershed becomes 0.

Determining stream flow and its routing using HEC-HMS

The process described in this part involved importing the sub-watershed curve number values determined using the WMS and the precipitation data developed for each sub-watershed using the HEC-HMS. The pieces of information imported from WMS were saved under different files for use in HEC-HMS. The functional activities performed in HEC-HMS include computing relevant GIS attributes and importing the NRCS curve number values for each sub-watershed. These pieces of information and the event rainfall in each sub-watershed were used to calculate the surface runoff and construct the hydrograph for each sub-watershed using the Aquaveo models. Then, the runoff and stream flow hydrographs from each sub-watershed were routed downstream from one sub-watershed to the next in a cascading fashion to determine the accumulated peak flow rates and total amounts of stream flows at the bottom of the watershed.

RESULTS

The main objective of the study leading to this paper was to use the HEC-HMS and WMS rainfall-runoff model to generate amounts of surface flows and peak flow rates from ungagged semi-arid watersheds. We used the Black Creek watershed in southeast Navajo Nation to demonstrate calculating a stream flow from a large watershed in the absence of adequate measured precipitation and other biophysical watershed characteristics data. Since the method required compartmentalizing of the large watershed into small sub-watersheds to make it appropriate for using the HEC-HMS and WMS, we had to estimate every sub-watershed rainfall data from that measured by the gage at Bonito sub-watershed. This was done for two daily

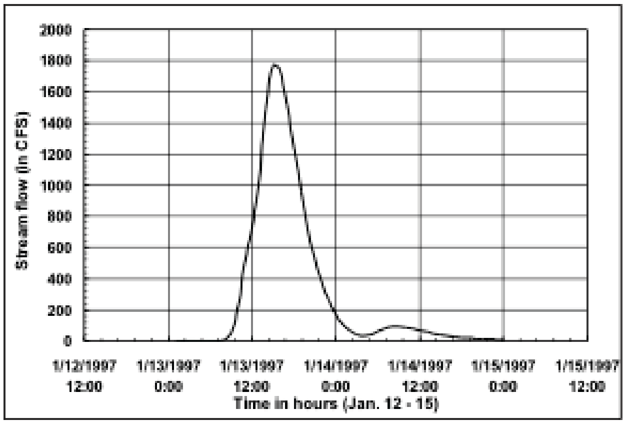

Figure 5. HEC HMS and WMS determined stream flow hydrograph from January 13, 1997 rainfall storm event.

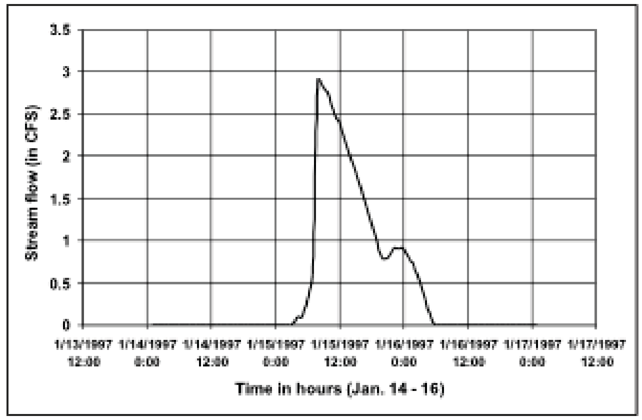

Figure 6. HEC HMS and WMS determined stream flow hydrograph from the January 14, 1997, rainfall storm event.

rainfall storm event amounts. The two storm rainfall events were 1.1 inches and 0.6 inches that fell on January 13 and 14, 1997, respectively.

Figures 5 and 6 are the HEC-HMS determined stream flow hydrographs produced from the storm events of January 13 and 14, 1997, respectively. The peak flow rate from the January 13 rainfall storm event is 1770 cubic feet per second (cfs) while that from the January 14, 1997, rainfall storm event is 2.9 cfs. The peak flow from the first storm event is probably somewhat higher for the watershed, due to possible errors when extrapolating precipitation data from one sub-watershed to the others. A second possible source of error is from the rough approximation of watershed characteristics. A third possible source of error may come from the WMS and HEC-HMS model inaccuracies. The hydrograph from the second storm is small but appropriate for the watershed, which seems to be similar to many observed wet period stream flows.

CONCLUSIONS

In the absence of measured stream flow data for all aspects of decision-making related to stream hydrology, indirect estimation of stream flow from precipitation storm events is very useful and quite appropriate. This approach can be done either through direct step-by-step rainfall-runoff modeling approach, or using commercially available programs such as the HEC-HMS and WMS used in this paper or others like the NRCS TR-20 and TR-55 (Hans et al., 1982) available at http://www.bossintl.com/snet-tr-20-program-tr-55-hydrology.html). However, in spite of their usefulness and importance in many instances, all indirect estimation methods are prone

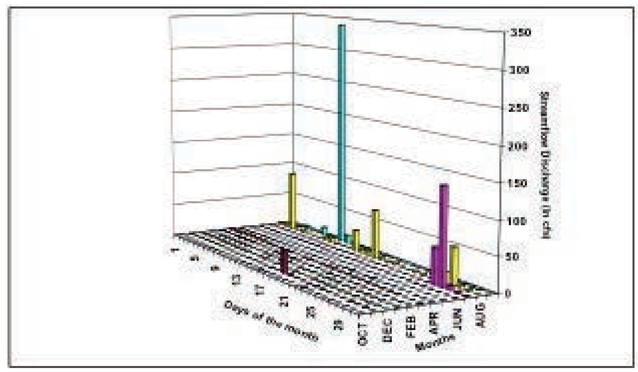

Figure 7. Daily stream flow rates (in cfs) at the Black Creek gaging station, Navajo Nation

to have some estimation error and uncertainties.

The above problems could be due to data inadequacy and model weakness. The result of the modeling effort used in this study is not free from these and other challenges. For this reason, we always recommend modelers to attempt to obtain and use best-fit models as well as have the necessary data sets carefully collected and well-prepared. In this study, the authors thought that there were adequate historical stream flow data available from the stream flow gaging station at the mouth of Black Creek watershed that would match with available rainfall storm events. To our surprise, in spite of the presence of a functioning stream gage since 1986, there were not any measured stream flows that match with any precipitation storm events. Hence, we could not verify the resemblance of the model-generated stream flow hydrographs with observed stream flow hydrograph for the same time period. Instead, we used year-round daily stream flow data (see Figure 7), taken in a different year, to demonstrate the appropriateness and application of using the modeling effort to the study area. However, to have a direct comparison, we recommend that gaging station stream flows are consistently and appropriately collected and processed for many years to be of use in modeling as well as to provide needed information for use by water resources personnel and other water interested parties.

In spite of some weaknesses, the modeling effort made in this study should be of value to describe the hydrology of the watershed as well as indicate the possible applicability of the model to other watersheds in the Navajo Nation and elsewhere. The HEC-HMS and WMS software available from Aquaveo is useful. However, there is lack of clear guidelines from the vendors to make it more readily applicable; and its extensive usefulness depends on clear communication and good interaction between users and the vendors.

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