Journal of Hydrology 584 (2020) 124309

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Commemorating the 50th anniversary of the Freeze and Harlan (1969) *Blueprint for a physically-based, digitally-simulated hydrologic response model*

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ARTICLE INFO

Keywords:
Freeze and Harlan (1969) Blueprint
Integrated hydrologic modelling
Blueprint
Hydrologic response model
Groundwater
Surface water
Historical note

ABSTRACT

The year 2019 marks the 50th anniversary of a pioneering publication in hydrology. Allan Freeze and Richard Harlan published their *Blueprint for a physically-based, digitally-simulated hydrologic response model* (Freeze and Harlan, 1969) in this journal. Their vision was for a futuristic model that would integrate key processes and compartments in the hydrologic cycle: precipitation, evapotranspiration, overland runoff, infiltration and groundwater exchange (into and out of) surface water bodies, such as rivers and lakes. Today, the original Blueprint is a reality. Our paper commemorates the 50 year anniversary of the original Blueprint paper. Through personal communications with Allan Freeze, we document the history and genesis of this paper for the first time. We reflect on the uptake of the Blueprint into modern hydrology, the development of numerical models that enabled this, and the range of challenges being tackled by these models. Finally, we consider challenges and opportunities for the future of this area of modelling and hydrologic science.

1. Prologue

The year 2019 marks the 50th anniversary of a pioneering publication in hydrology. Allan Freeze and Richard Harlan published their *Blueprint for a physically-based, digitally-simulated hydrologic response model* (Freeze and Harlan, 1969) in this journal. The paper by Freeze and Harlan described a blueprint vision for a physically-based, digitally-simulated hydrologic response model. Their vision was for a futuristic model that would integrate key processes and compartments in the hydrologic cycle: precipitation, evapotranspiration, overland runoff, infiltration and groundwater exchange (into and out of) surface water bodies, such as rivers and lakes. This integrated model would be fully-coupled, spatially-distributed, and physically-based. It was a dream – an “artist’s conception” – as the original authors put it. Today, the original Blueprint is a reality. Numerical models have been developed that employ the very vision set out by Freeze and Harlan back in 1969. This new generation of numerical models has enabled a concomitant explosion in integrated hydrologic modelling, allied hydrologic research and practical applications, as evidenced in the review by Paniconi and Putti (2015). Numerical models based on the Blueprint include CATchment HYdrology model (CATHY) (Camporese et al., 2010), MODFLOW-based Hydrologic Modelling System (MODHMS) (Panday and Huyakorn, 2004), HydroGeoSphere (Aquanty.com; Aquanty, Inc., 2018), the Integrated Hydrological Model (InHM) (VanderKwaak, 1999; VanderKwaak and Loague, 2001), OpenGeoSys (https://www.opengeosys.org/; Kolditz et al., 2012), GEOtop (Rigon et al., 2006), ParFlow (Kollet and Maxwell, 2006), GETFLOWS (https://www.getc.co.jp/), Criteria-3-D (Bittelli et al., 2010) and MIKE SHE (Abbott et al., 1986; Graham and Butts, 2005) to mention just a few. It is interesting to note that “SHE” is the acronym Système Hydrologique Européen (European Hydrological System). It was developed by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (a consulting firm in France). SHE is fully consistent with Freeze and Harlan’s (1969) Blueprint. Other early papers (Girard et al., 1981; Villeneuve et al., 1982) are also consistent with Freeze and Harlan's Blueprint. These papers were published in French, as a cooperation between French and Québec researchers. They demonstrate that it was not only the English-speaking community that was interested in integrated hydrologic modelling.

Recent model intercomparison studies provide a synopsis of a number of contemporary integrated surface-subsurface flow models (Maxwell et al., 2014; Kollet et al., 2017). Maxwell et al. (2014) discuss the important differences in coupling strategies and solution techniques that are employed by integrated models.

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https://doi.org/10.1016/j.jhydrol.2019.124309
Received 7 September 2019; Received in revised form 30 October 2019; Accepted 31 October 2019

Our paper commemorates the 50 year anniversary of the original Blueprint paper. Through personal communications with Allan Freeze, we document the history and genesis of this paper for the first time. We reflect on the uptake of the Blueprint into modern hydrology, the development of numerical models that enabled this, and the range of challenges being tackled by these models. These challenges range from fundamental and theoretical discoveries about hydrologic processes to advanced applications that support water resources management. Finally, we consider challenges and opportunities for the future of this area of modelling and hydrological science. This paper is deliberately strategic, philosophical, historical and prospective. We highlight some key points in the scientific evolution of this field and discuss their significance. It is not a comprehensive review and references cited are therefore demonstrative rather than exhaustive.

2. Genesis of the Blueprint (circa 1968–1969)

We begin with an historical account of the genesis of the paper, which is faithfully reproduced from discussions and written communications we have had directly with Allan Freeze, one of the original Blueprint authors. His co-author, Richard Lee Harlan, passed away in 2011. We provide first-person personal communications from Allan Freeze to enable historical veracity and authenticity.

According to Allan Freeze, also a co-author of the widely known textbook *Groundwater* (Freeze and Cherry, 1979), “Dick Harlan and I met serendipitously, not through any official professional connection, but because he and his wife Sandra, and my wife Donna and I, lived in the same apartment building in Calgary, Alberta. We were both new to Calgary, and both of us were living temporarily in the apartment while we awaited the completion of our new houses, both then under construction. I had worked as a research scientist for the federal groundwater group for a few years and had recently been posted to the Calgary office (at that time part of the Department of Energy, Mines and Resources, later to be annexed into Environment Canada). Dick was an American (from Michigan, if I remember correctly) who had just been hired as a research hydrologist with the Department of Forestry and Fisheries. So, we did not work for the same agency, but our offices were close together, and we often carpooled to work together. It was during these rides that we discovered our mutual interest in computer simulations of hydrologic processes, and began talking about the issues that eventually led to our joint paper.

The main contribution of the paper in my opinion was in getting hydrologists of all stripes interested in meeting and working with each other. Modern researchers will find it quaintly amusing how little interaction there was in 1969 between groundwater and surface water hydrologists. Each lived on their own desert islands: separate associations; separate associate editors at *Water Resources Research* and *Journal of Hydrology*; separate sessions at the American Geophysical Union Fall Meeting; and seldom the twain met. Even when I was editor of *Water Resources Research* from 1976 to 1980, I was always surprised at how naive the treatment of groundwater was in surface-water papers, and vice-versa. There were few papers that actually married the diverse components of the hydrologic cycle in any meaningful way. I think much credit should be given to Peter Eagleson of MIT and his book “Dynamic Hydrology” published in 1970 for turning the tide.” (see Eagleson (1970)).

R. Allan Freeze was born in Edmonton, Alberta, on May 23, 1939. He obtained both M.Sc. and Ph.D. degrees from the University of California, Berkeley. He worked for the Canadian government, the IBM Thomas J. Watson Research Center and was later a professor in the Department of Geological Sciences at the University of British Columbia. Freeze has received many awards for his work. He is a Fellow of the Royal Society of Canada, a member of the Canadian Academy of Engineering and a foreign member of the National Academy of Engineering in the US. He holds many other awards from professional societies. Freeze has wide-ranging interests and hobbies. He has published on the statistics of baseball batting orders (Freeze, 1974). He is also the author of two popular-science books: “The Environmental Pendulum: A Quest for the Truth about Toxic Chemicals, Human Health, and Environmental Protection,” (Freeze, 2000) and “The Fluoride Wars: How a Modest Public Health Measure Became America’s Longest-Running Political Melodrama,” (Freeze and Lehr, 2009).

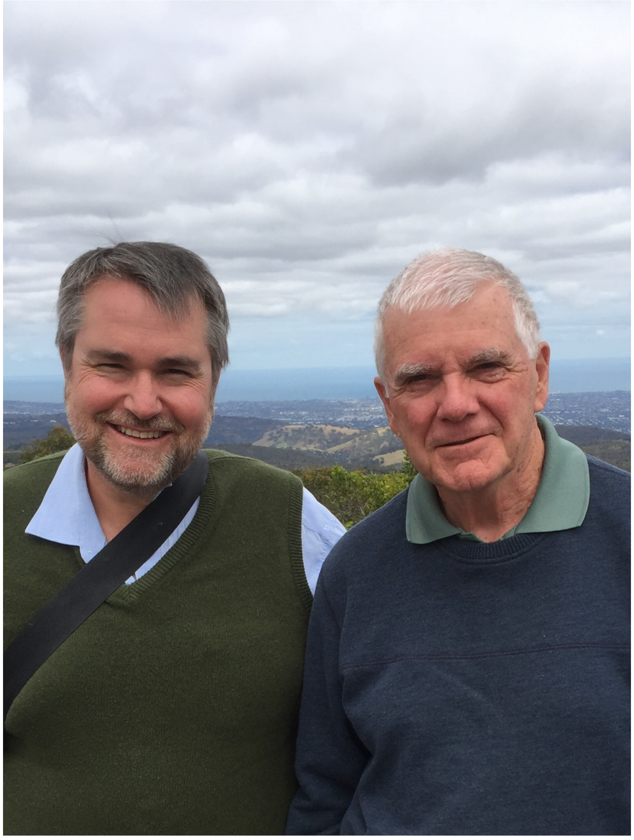


Fig. 1a. Allan Freeze (right) with Craig Simmons (left) – subject and author – in Adelaide, Australia, November 28, 2018.

Freeze also shared a little bit more about his recent history. He remarked, “I am alive and well in my retirement in Vancouver, still writing popular science as a hobby, golfing to a 14-handicap (not bad for a recently-turned octagenarian), and playing duplicate bridge regularly with my wife of 58 years. As for Dick, he left the research world a few years after our joint paper, and worked for several years for a consulting engineering company in Denver, Colorado. Sadly, he passed away many years ago at much too early an age.” Fig. 1a shows Allan Freeze and Craig Simmons on November 28, 2018, in Adelaide, Australia.

Freeze also provided us with some information on Dick Harlan and their connection following the publication of the Blueprint. Freeze described the period following the Blueprint paper, “There is very little further of a joint biographical nature to disclose. Shortly after our “Blueprint” paper, I moved from Calgary to join the IBM Thomas J. Watson Research Center in Yorktown Heights, NY, and although we kept in touch, we never did any joint work again.”

We were able to glean a bit more information on Dick Harlan from Allan Freeze and from Dick Harlan’s online obituary (https://horancares.com/obits/richard-l-harlan/). Richard Lee Harlan, was born in Denver, Colorado, on July 7, 1939, and died Nov 15, 2011 (age 72). He obtained his Ph.D. in hydrogeology from Michigan State University. He worked in Calgary, Alberta, and Ottawa, Ontario, for the Canadian Department Forestry and Fisheries for 15 years. He then worked for 11 years as Chief Hydrogeologist in the Denver, Colorado, office of the American consulting firm Dames and Moore. Dick Harlan

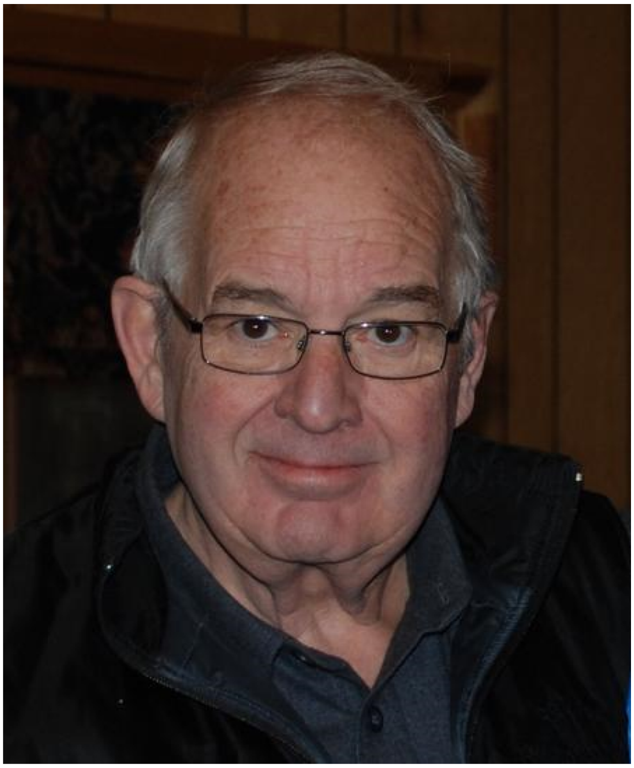


Fig. 1b. Richard L. Harlan (July 7, 1939 – November 15, 2011). Photo from his online obituary, likely circa 2009–2011. (https://horancares.com/obits/richard-l-harlan/).

was American and Freeze remarked in communications with us that he was not sure why or how Harlan decided to come to Canada. A copy of the picture of Harlan from the online obituary is found in Fig. 1b. We are not sure of the exact year this photo was taken. From discussions with Freeze, we guess that it was probably taken a year or so before Harlan's death in 2011.

3. Realising a Dream: The Last 50 Years (1969–2019)

Freeze and Harlan had a dream as they carpooled. They imagined a virtual hydrologic laboratory – a physically-based digital modelling world – where important hydrologic processes and groundwater flow and surface water flow (rainfall, evaporation, runoff, recharge to groundwater) could be modelled at a hydrologic basin scale. Their original paper was concerned with flows and hydraulics – water quantities, rates and flow pathways. Fig. 2 shows the abstract from the original paper. Fig. 3 shows Fig. 2 from Freeze and Harlan (1969) illustrating a hydrologic basin and a three-dimensional nodal grid of that hydrologic basin – a graphic form that nicely captures the overarching vision set out in the original Blueprint paper.

Freeze and Harlan (1969) were clear about their motives. Their purpose was not to create an "emotional pitch for a pet methodology" but rather "to examine the *possibility* of creating physically-based hydrologic response models" (italics are Freeze and Harlan's own emphasis). They noted that a complete simulator for the hydrologic cycle "tantalizes most hydrologists". But they also observed issues and limitations, drawing upon comments from Amorocho and Hart (1964) and Crawford and Linsley (1966). These limitations included a lack of knowledge of physical hydrology and component phenomena as well as the prohibitive amounts of input data that would be required to realise the Blueprint in practice. They conceded that their paper was "more of an "artist's conception" than a true "blueprint"" (Freeze and Harlan, 1969, p. 238).

To appreciate the computational vision implicit in the original Blueprint, one must imagine the time when Freeze and Harlan wrote this paper. The first paper to present a digital groundwater model was by Tyson and Weber (1964). George Pinder and John Bredehoeft had also just published a paper on the development of a digital groundwater model (Pinder and Bredehoeft, 1968). Their model was verified using electrical (low pass RC filter) analogs for groundwater flow modelling that were still in vogue at the time. These were the waning days of electrical resistor–capacitor networks used to simulate groundwater flow. There is a classic photo of Arlan Harbaugh, co-author of the USGS model MODFLOW (McDonald and Harbaugh, 1988), simulating groundwater at Long Island, New York, with a big electrical resistor–capacitor network the size of a room (Fig. 4).

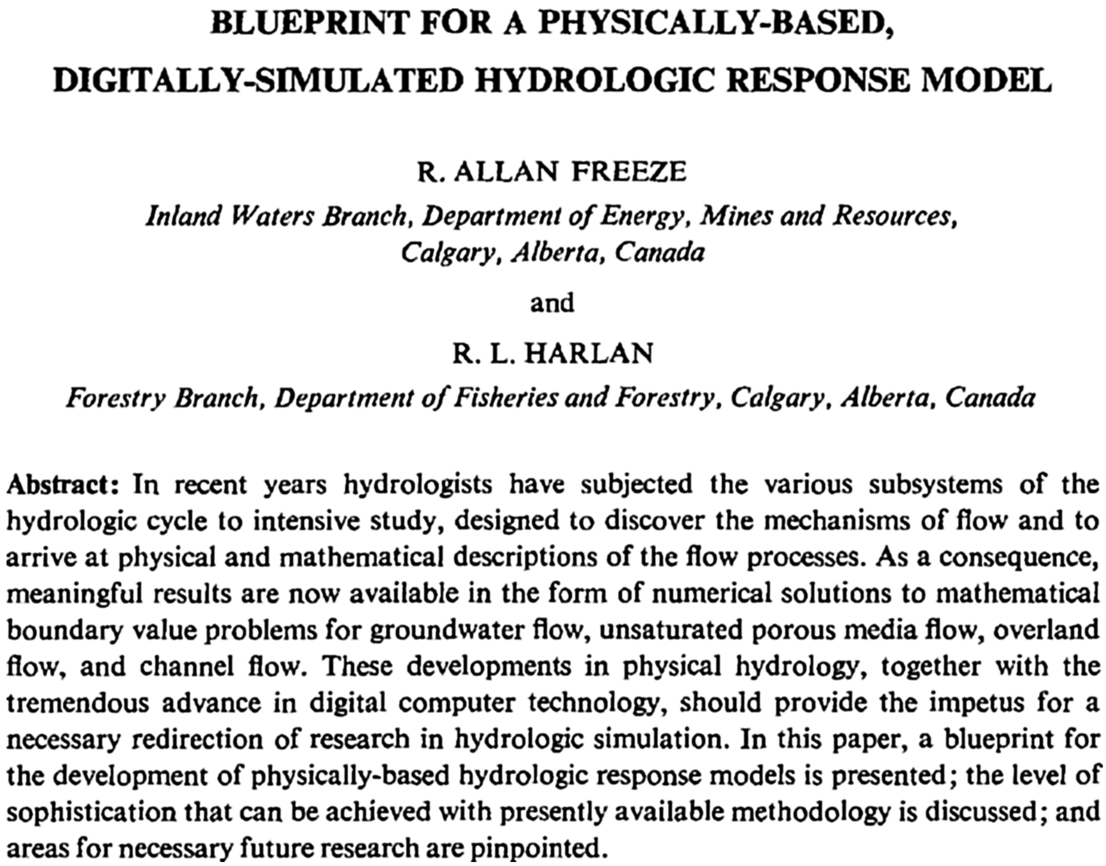
Freeze and Harlan noted that, based on Forsythe and Wasow (1960), a time-dependent (boundary value) problem in three dimensions could be tackled in moderate detail using a 100 × 100 × 100 nodal array. They went on to ask, "What then of the machines of the 1970's?". This prescient question anticipates the exciting future possibilities that growth in computer power was very likely to bring. It also suggests that the authors were aware of the distinct possibility that their 1969 "artist's conception" could become the real-world digital simulation of the future.

The earliest application of a Blueprint-based model was by Freeze (1972) for a synthetic catchment. The simulations were undertaken on the IBM 360/91 when Freeze was working at the IBM Thomas J. Watson Research Center at Yorktown Heights, New York. With a memory of 1.5×10^6 Bytes of storage, the IBM 360/91 was one of the most powerful computers then available. Nevertheless, the spatial extent of the flow domain was limited and only a coarse mesh could be employed. The first field application of this Blueprint-based model was to a hillslope in the Sleepers River catchment in Idaho (Stephenson and Freeze, 1974). Keith Beven (Beven, 1975) developed a model based on the Blueprint for his Ph.D. thesis and applied it to the small East Twin catchment in the UK. This model was based on a hillslope segment, width averaged, finite element solutions rather than the finite-difference structures presented in the Blueprint. This solution method enabled the hillslopes to look more like real hillslopes.

Since those earliest applications, the Blueprint has been implemented in a growing number of integrated numerical models. The surface–subsurface model intercomparison study by Maxwell et al. (2014) clearly explains the classification of coupled hydrologic models based on the solution technique or coupling strategy that is employed. They defined three approaches for solving the coupled system of equations i.e., the solution technique, namely: asynchronous linking, sequential iteration, and globally implicit. In terms of coupling strategy, they described three distinct formulations for integrating hydrostatic surface and subsurface flow, namely: first-order exchange, continuity of pressure, and boundary condition switching.

Integrated models have allowed progress on many scientific and engineering matters. They have been used to study a wide range of purely theoretical to highly applied problems. The application of the Blueprint includes the exploration of fundamental hydrologic phenomena to advance physical hydrology (Freeze, 1972; Beven, 1977; Brunner and Simmons, 2012) to the coupling among atmospheric, surface and subsurface processes (e.g., Davison et al. (2018)). An example of the exploration of hydrologic phenomena is the series of papers by Keith Loague and colleagues on the R-5 catchment, Oklahoma, where progressively more detailed event-based simulations were conducted, resulting in changes in the simulated near-surface response (Loague et al., 2005). Excellent review articles citing numerous studies ranging from water resources management to the coupling between soil, biota or the cryosphere, to mention a few examples, include Paniconi and Putti (2015).

One precondition for these applications was the significant increase in computational power. Kollet et al. (2010), for example, used 16,384 processors with about 8×10^9 (nearly 10 billion) grid cells to solve



**BLUEPRINT FOR A PHYSICALLY-BASED,
DIGITALLY-SIMULATED HYDROLOGIC RESPONSE MODEL**

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Abstract: In recent years hydrologists have subjected the various subsystems of the hydrologic cycle to intensive study, designed to discover the mechanisms of flow and to arrive at physical and mathematical descriptions of the flow processes. As a consequence, meaningful results are now available in the form of numerical solutions to mathematical boundary value problems for groundwater flow, unsaturated porous media flow, overland flow, and channel flow. These developments in physical hydrology, together with the tremendous advance in digital computer technology, should provide the impetus for a necessary redirection of research in hydrologic simulation. In this paper, a blueprint for the development of physically-based hydrologic response models is presented; the level of sophistication that can be achieved with presently available methodology is discussed; and areas for necessary future research are pinpointed.

Fig. 2. The original abstract from the Freeze and Harlan (1969) Blueprint. The motivations for the paper are clearly articulated. Reprinted from *Journal of Hydrology*, 9, Freeze, R. A., and Harlan, R. L., Blueprint for a physically-based, digitally-simulated hydrologic response model, 237–258, Copyright (1969), with permission from Elsevier.

what is essentially the “Freeze and Harlan Problem”. Their application was for a watershed on the order of 10^3 km^2. Expansions and extensions of the original Blueprint have also been proposed. For example, Partington et al. (2017) proposed a framework to couple sedimentological, hydrological and hydrogeological processes in streambeds.

The Blueprint has not been without controversy, criticism and debate (Loague and Ebel, 2016). Earliest model applications in real field settings were not particularly successful (Stephenson and Freeze, 1974; Beven, 2001, 2002). Stephenson and Freeze (1974) were amongst the earliest scientists to document challenges with the validation of hydrological models (Beven, 2002). Beven (2002) questioned the suitability of the Blueprint to simulate hydrological response functions. More specifically, Beven (1989, 2002) states that Darcian theory, and in particular the Richards equation, are not appropriate to describe unsaturated subsurface flow at large scales because of heterogeneity and preferential flow paths. Beven (2002) does not really argue against the Blueprint as a conceptual framework for catchment modelling in terms of processes, he argues against the suitability of the commonly used continuum differential equations in implementing that framework. There are clearly scales where the continuum approach (Darcian implementation) simply will not work. The assumption that small-scale measurements apply at any scale is also clearly problematic.

Beven and Germann (2013) note that numerous extensions to Richards equation have been proposed to account for preferential flow, but that there is no rigorous physical underpinning to Richards equation and that “bolting” on preferential flow capabilities is thus problematic. We still have no generally applicable – scale-independent – description of soil water flows that can be considered adequate – continuum or not. A universal, scale-independent description for dealing with such scaling would be an important evolution of the Blueprint.

However, the main contribution of the Blueprint was to couple the surface with the subsurface in order to overcome the conceptual separation between the two hydrologic domains. Extending or replacing the conceptualization of individual processes such as unsaturated flow, evapotranspiration, infiltration, even groundwater flow or the coupling between the surface and subsurface domain would constitute an evolution of the Blueprint and its primary strategic intent. Changing the individual constituent process descriptions does not, ipso facto, undermine or invalidate the principal philosophy or motivation of the Blueprint. Strictly speaking, however, whether the original Blueprint is undermined or invalidated depends on whether one considers the Blueprint to be intrinsically linked to continuum differential equations – a *continuum* Blueprint – or not, and the mathematical formulations presented in the original Blueprint. We do not see them as intrinsically linked. Our view appears to be consistent with Freeze’s own view when he remarks, “The purpose of the paper was not to get every mechanism in the hydrologic cycle dead-to-rights, but rather to promote more-integrated treatments.” We also assert that there are many situations where the continuum approach is valid and effective. Numerous modelling studies, several of which are described in this paper, demonstrate that integrated modelling produces results that are consistent with observations at the representative scale of the problem under consideration. Obviously integrated modelling that applies the Blueprint philosophy must always exercise care and caution. An appropriate objective for the study and the model that is employed must be defined. The model’s formulation and assumptions (including conceptualisation and governing equations) must clearly be appropriate to ensure robust and reliable results that meet the modelling objectives and to ensure consistency with observations at the scale of interest. This applies to all modelling and not just integrated modelling.

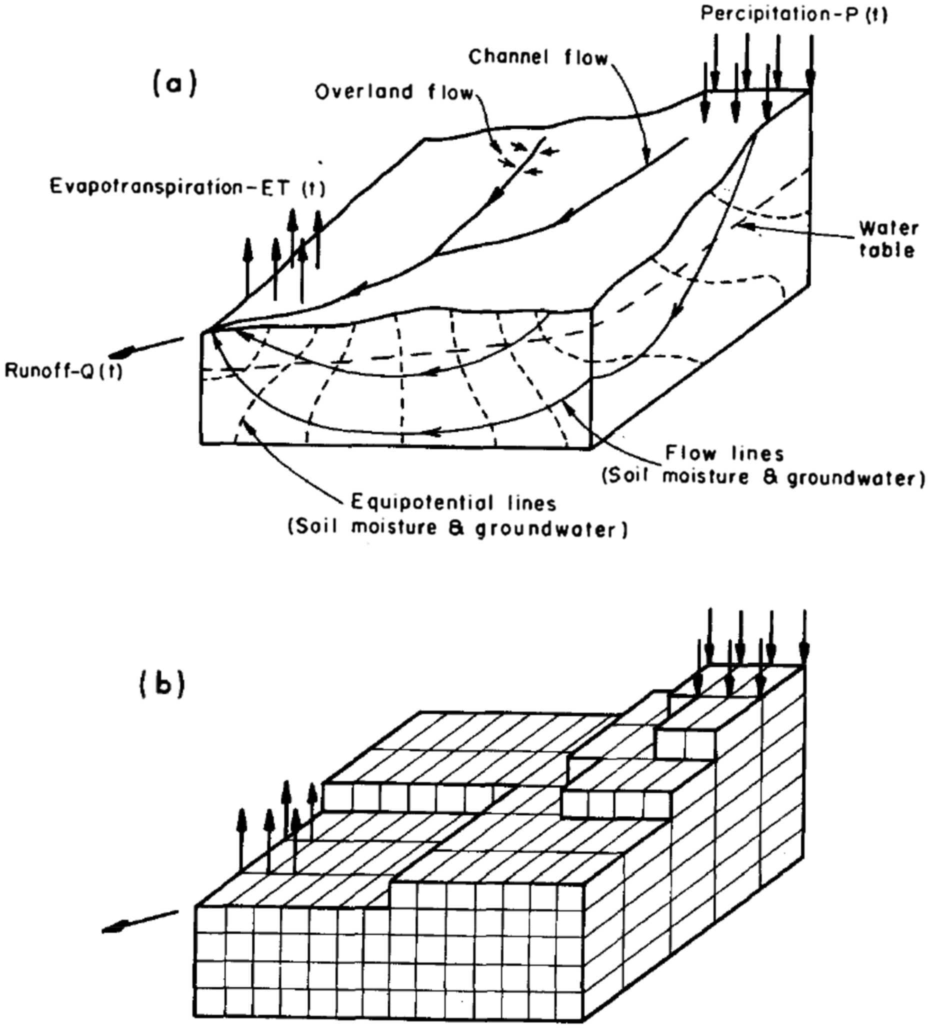

Fig. 3. Schematic diagram of (a) Hydrologic basin and (b) Three dimensional nodal model of hydrologic basin.

Fig. 3. Original figure from Freeze and Harlan (1969) Blueprint paper showing a conceptual hydrologic basin and a three-dimensional grid of that basin (Fig. 3 from Freeze and Harlan (1969)). Reprinted from *Journal of Hydrology*, 9, Freeze, R. A., and Harlan, R. L., Blueprint for a physically-based, digitally-simulated hydrologic response model, 237–258, Copyright (1969), with permission from Elsevier.

Beven (2002) also criticizes the term "physically based". While acknowledging that the Blueprint is derived deductively from established physical principles, he highlights that "'Physically based' should also imply consistency with observations" – which, according to Beven, is not the case for the Blueprint-based models. Beven (2002) speculated that the original Blueprint, or perhaps more specifically the continuum differential equation approach presented in the original Blueprint, will eventually be abandoned. Beven (2002) proposed the concept of an "Alternative blueprint" which "is consistent with observations at the scale of interest". Recent review papers (Paniconi and Putti, 2015; Barthel and Banzhaf, 2016; Clark et al., 2017) on Blueprint-based models, however, indicate that there are a growing number of applications linked to observable field data, in addition to the application of Blueprint-based models to explore fundamental physics. The significant developments in data acquisition, data assimilation (Kurtz et al., 2017) and the subsequent integration with model calibration (Schilling et al., 2019) will certainly continue in the future. Data assimilation (and model surrogacy) can be a way of correcting and compensating for a model's deficiencies – as is regularly done in weather forecasting. It is useful for operational purposes. However, data assimilation and computational advances cannot, by themselves, be the basis for understanding and advancing fundamental physics.

Although numerous challenges clearly do remain, current citation data and contemporary applications suggest growth in the interest and importance of spatially-distributed, physically-based hydrologic modelling. Citation data for Freeze and Harlan (1969) plotted as cumulative citations over time (Fig. 5) show a large growth in citations with time. The data in this figure were accessed from Google Scholar on 6 September 2019 when the total citation count was 736.

There are increasing numbers of sophisticated applications and examples of integrated hydrologic modelling. Engdahl and Maxwell (2015) evaluated changes in the spatial distribution and flow-paths of water in a high-mountain, headwaters watershed using an integrated hydrologic model based on a heterogeneous domain in the Rocky Mountains of Colorado in the United States. The simulations were performed using the ParFlow model (Kollet and Maxwell, 2006). Fig. 6 shows the hydraulic conductivity field in the model domain and simulated ponded water depth (stream gauge) for the base case scenario studied. Hwang et al. (2019) estimated the influence of cumulative wastewater treatment plant discharge on acesulfame, an artificial sweetener, and *Escherichia coli* in the mixed-use, highly impacted Grand River Watershed, Ontario, Canada, using a fully-integrated modelling

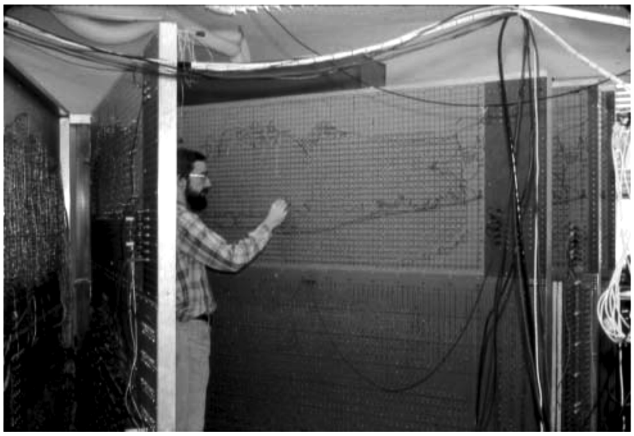

Fig. 4. Arlen Harbaugh, co-author of MODFLOW, in 1975 making a voltage measurement on the three-dimensional electric-analog model of Long Island, New York (Fig. 2 from Reilly (2004)). Reprinted from *Ground Water*, 42(4), Reilly, T.E., A Brief History of Contributions to Ground Water Hydrology by the U.S. Geological Survey, 625–631, Copyright © 2004 John Wiley & Sons, Ltd., with permission from John Wiley and Sons.

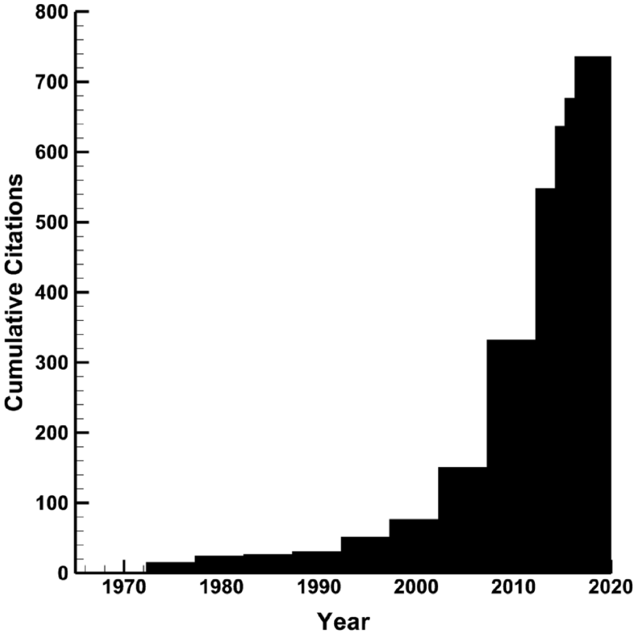

Fig. 5. Citation data – shown as cumulative citations over time – for the Freeze and Harlan (1969) Blueprint paper. Data were obtained from Google Scholar on September 6th, 2019. On this date, the Freeze and Harlan (1969) paper had a total citation count of 736 citations.

approach. The simulations were performed using HydroGeoSphere (Aquanty.com; Aquanty, Inc., 2018). 70% of the land area in the Grand River Watershed is used for agriculture. It has a population of about one million people and there are 28 municipal wastewater treatment plants in the watershed. The study by Hwang et al. (2019) is the largest-scale integrated transport problem of which we are aware. Fig. 7 shows the location of the watershed, watershed topography, and a subsection of the spatially-varying finite element mesh within the 3D HydroGeoSphere model. The model reproduces observations. Fig. 8 shows the simulated acesulfame concentrations along the length of the Grand River demonstrating excellent agreement between simulated and measured concentrations. Chen et al. (2019) developed an integrated hydrologic model for continental Canada using HydroGeoSphere that covers approximately 10.5 million km^2. As a continental-scale application it is one of the largest-scale applications of integrated hydrologic modelling of which we are aware. The model reproduces observations. The model results are in very good agreement with observations of groundwater levels, surface water flow rates and lake levels. This powerful modelling study demonstrates that large-scale, fully-integrated hydrologic modelling is possible and that it can be successfully used to quantify components of a large-scale water balance, which are difficult or impossible to quantify without modelling. Fig. 9 shows a close-up look at the 3D triangular prism grid along the Great Lakes region in this HydroGeoSphere model. The model includes significant topographic relief. The irregular triangular mesh is refined along major rivers and at the lake shore. InHM (VanderKwaak, 1999; VanderKwaak and Loague, 2001) simulations for the small rangeland catchment known as the R-5 catchment are shown in Fig. 10 (Loague et al., 2005). This figure illustrates the spatial and temporal information generated using a physically-based model that can be used to identify processes. Simulated hydrographs and surface soil–water content through space and time are shown. Simulated hydrographs are compared with an observed hydrograph. Loague et al. (2005) remarked: “Physics-based models have great diagnostic and forensic capabilities.” The integrated and distributed response of a coupled surface–subsurface hydrological model for the des Anglais catchment, Quebec, was simulated with the CATHY model (Camporese et al., 2010) by Sulis et al. (2011a). Climate change impacts were assessed in the same catchment with a detailed hydrological model of surface–subsurface interactions and comparison with a land surface model (Sulis et al., 2011b). Fig. 11 shows good agreement between the observed and simulated discharge at streamflow gauges in the catchment for the verification period. The model employed by Sulis et al. (2011a) and Sulis et al. (2011b) is another example of a model that reproduces observations.

All of these recent studies, and many others not shown here, demonstrate that 3D fully-coupled, spatially-distributed, integrated hydrologic modelling is tractable, reliable, robust, practical and useful. It is also efficient and effective at large scales. It is fascinating, and perhaps a little amusing, to compare the contemporary, actual model domains and model discretisations in recent studies with the now quaint, seemingly hand-drawn original conceptualisation and digital model – the “artist’s conception” – shown in Fig. 3 of the original Freeze and Harlan Blueprint (Fig. 3 of this paper). Put side by side, the comparison of the modern digital implementation with the original hand drawings in the Freeze and Harlan Blueprint is quite striking.

As Freeze and Harlan (1969) stated, and we echo here, our aim is not to promote a pet methodology or a pet Blueprint – but simply to recognise one approach that deserves increasing attention as part of the Hydrologists’ Toolbox (Simmons et al., 2012). Interestingly, the original Blueprint clearly articulated the various methods of hydrologic simulation based on Amorocho and Hart (1964), which include physical models, physically-based mathematical methods, parametric methods and stochastic methods. Lumped and distributed models, both spatially and sequentially, were also mentioned by Freeze and Harlan (1969). All of these models and approaches have a time and place in the practice of hydrology.

4. Future Challenges, Opportunities and New Horizons

The Freeze and Harlan (1969) Blueprint has laid the foundations for an entire discipline of hydrologic science (i.e., watershed modelling) and a new generation of computer codes to simulate hydrologic phenomena. As Freeze and Harlan (1969, p. 242) noted, “If the model we espouse is to offer promise for the future, it must be able to compete with the systems approach in terms of practical results and utility. A case could then be made for its superiority on the basis that a better understanding of the internal processes and their effects on the overall hydrologic system is desirable and could be beneficial to the solution of practical problems.” We contend that the Blueprint is currently practical and useful. The prognosis for its continued and increasing use in the future is promising (Berg and Sudicky, 2019). It provides a robust,

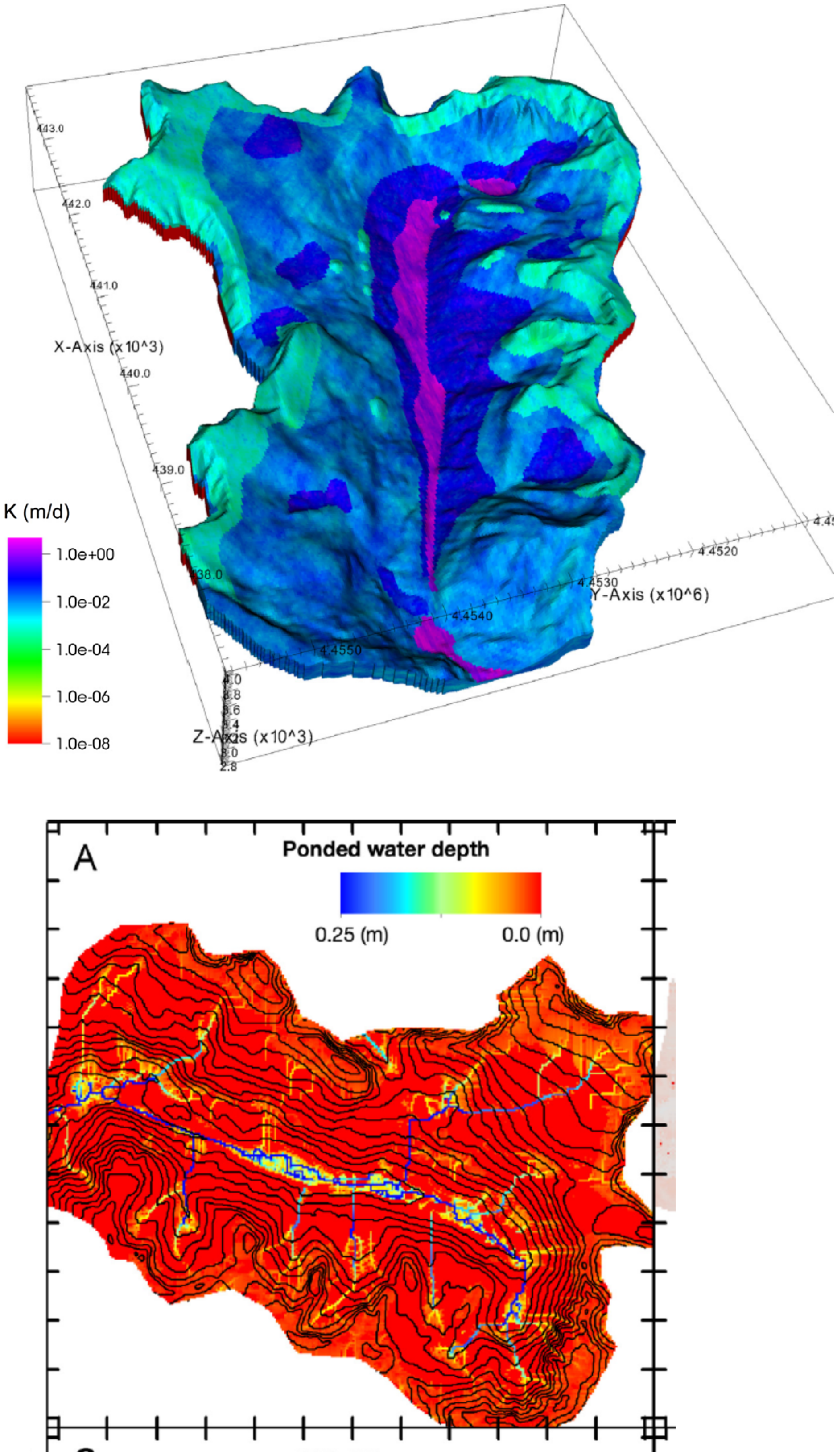

Fig. 6. Top: Hydraulic conductivity in the model domain. Bottom: Ponded water depth in the top layer (i.e., stream stage) for the base case scenario modelled using ParFlow in the Rocky Mountains, Colorado, watershed study (Fig. 2 and Fig. 3a from Engdahl and Maxwell (2015)). Reprinted from *Journal of Hydrology*, 522, Engdahl, N., and Maxwell, R., Quantifying changes in age distributions and the hydrologic balance of a high-mountain watershed from climate induced variations in recharge, 152–162, Copyright (2015), with permission from Elsevier.

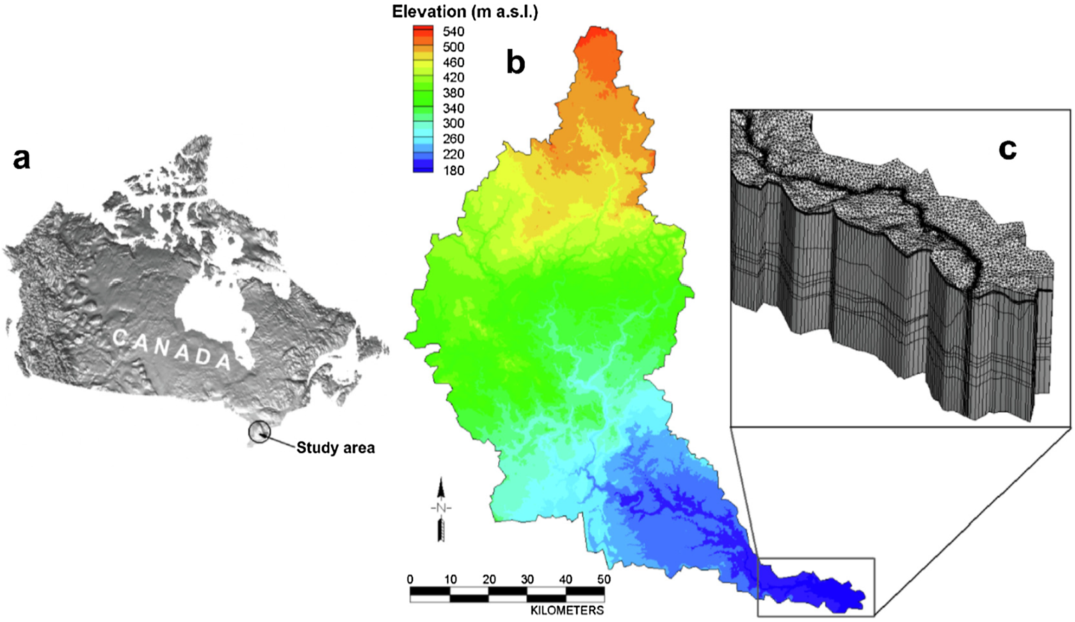

Fig. 7. (a) Location of the Grand River Watershed in Canada, (b) watershed topography, and (c) a subsection of the spatially-varying finite element mesh within the 3D HydroGeoSphere model (Fig. 1 from Hwang et al. (2019)). Reprinted from *Water Research*, 157, Hwang, H.-T., Frey, S.K., Park, Y.-J., Pintar, K.D.M., Lapen, D.R., Thomas, J.L., Spoelstra, J., Schiff, S.L., Brown, S.J., and Sudicky, E.A., Estimating cumulative wastewater treatment plant discharge influences on acesulfame and *Escherichia coli* in a highly impacted watershed with a fully-integrated modelling approach, 647–662, Copyright (2019), with permission from Elsevier.

tractable, defensible and reliable ideological foundational basis for the development of integrated hydrological modelling and hydrological science. The ways in which it is implemented – through constituent processes and compartments and the vital coupling between them – will necessarily continue to evolve.

There are enormous challenges and opportunities for this field of hydrological science. Many of these challenges and opportunities have been described elsewhere by others, perhaps in different words, but it is useful to summarise some salient points here as we reflect and prospect on the Blueprint.

Whilst the Blueprint is seminal it is not timeless. It was an idea. As Freeze himself noted in personal communications with us, a main motive and contribution was to get disparate fields of hydrology – groundwater and surface water hydrologists and soil scientists and atmospheric scientists – talking and working together and “to promote more-integrated treatments.”

The original Blueprint noted challenges with data acquisition as well as our knowledge of physical hydrology and the individual hydrologic compartments. Whilst there have been many scientific advances in physical hydrology, many of the problems noted in Freeze and Harlan (1969) remain true today. Our scientific knowledge is incomplete. We still grapple with issues including, for example, heterogeneity, and if and how to include small-scale details in large-scale models. Research that followed the advent of the Blueprint has clarified the complexities of subsurface storm-flow to streams (preferential flow paths, etc). The Freeze and Harlan (1969) conceptual model is therefore now recognized as a somewhat simplistic first pass. There are clearly situations, as outlined earlier, where the continuum approach does not work. Addressing the limitations of the original *continuum* Blueprint are amongst the exciting and important areas for future research. Heterogeneities and preferential flows are not the only issues; turbulent flow in karstic systems and influences of vegetation on changing soil and surface properties also need to be addressed. These issues, and how they are addressed, will depend on a number of matters including, for example, the nature of the questions and problems that are being tackled, the associated spatial and temporal scales, whether one is dealing with a flow or transport problem, and whether the system is transient or in steady state.

We have more data now than ever, often in the public domain, and there are papers showing the enormous potential to incorporate field-based methods, geochemistry and environment tracers (Schilling et al., 2017), geostatistics, parameter estimation techniques and uncertainty analysis (Berg et al., 2019a; Miller et al., 2018) into fully-coupled, physically-based, spatially-distributed models (Brunner et al., 2017).

High-performance computing and new types of data will be mainstays in the future of hydrologic science and the ever-increasing uptake, development, application and evolution of the Freeze and Harlan (1969) Blueprint. Our models are more computationally demanding now than ever. Yet, recent strides in computational methods, code parallelization and cloud computing have already enabled real-time 3D forecasting of the surface and subsurface hydrologic regimes over large watersheds in an operational mode, as driven by an ensemble of weather forecasts (Berg et al., 2019b). We anticipate the next generation of models with increased capabilities as codes such as HydroGeoSphere (Aquanty.com; Aquanty, Inc., 2018), MIKE SHE (Abbott et al., 1986; Graham and Butts, 2005) and ParFlow (Kollet and Maxwell, 2006) continue to evolve.

Parameter estimation, uncertainty analysis, data assimilation and data worth studies underpin smart, efficient and effective data collection and modelling strategies. They underpin risk-based environmental decision making. They involve massive amounts of model-generated data. Determining appropriate model simplicity-complexity is an ever-present and ongoing challenge.

More data are becoming available for use in groundwater modelling and as vital input to the 21st century physically-based digitally-simulated hydrologic response model. New and exciting extraordinary datasets are being collected: from satellites (e.g., Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) data for tracking Earth’s water movement across the planet, including underground water storage) and rich GIS datasets for vegetation and soil types that have millions of data points in a layer. “Big data” – perhaps something we thought we would never need to worry about in surface/subsurface hydrologic science – is something that we must now wrangle.

The purpose of the hydrologic response model developed by Freeze and Harlan (1969) was noted early in the original paper. They were principally concerned with “hydrologic events” and natural and

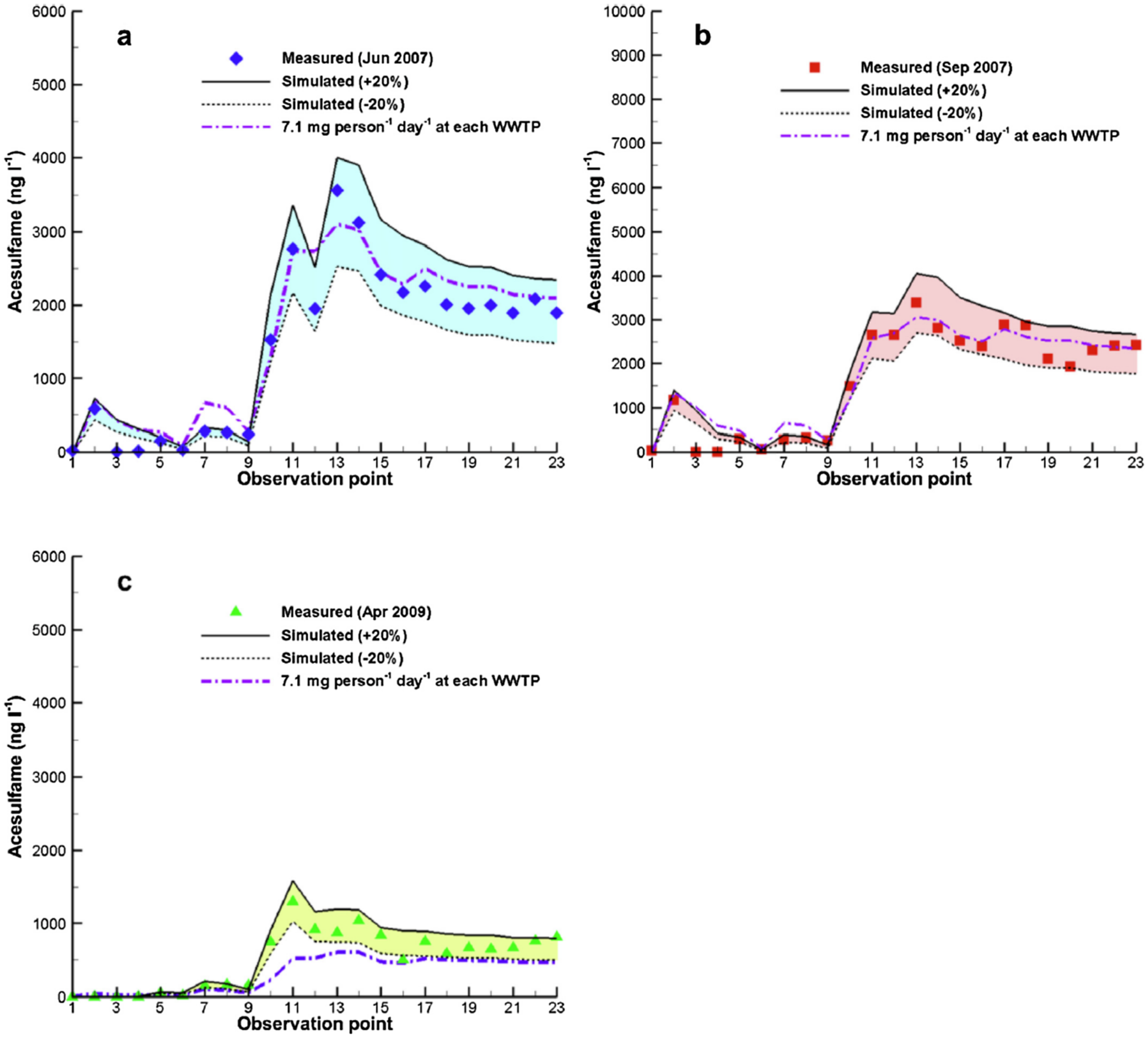

Fig. 8. Simulated acesulfame concentrations along the length of the Grand River where base loading rates (7.14 mg person^{-1} day^{-1}) and adjusted loading rates were employed in the (a) June 2007 (low flow), (b) September 2007 (low flow), and (c) April 2009 (high flow), steady-state hydrologic conditions. Simulations were performed using the 3D HydroGeoSphere model (Fig. 7 from Hwang et al. (2019)). Reprinted from *Water Research*, 157, Hwang, H.-T., Frey, S.K., Park, Y.-J., Pintar, K.D.M., Lapen, D.R., Thomas, J.L., Spoelstra, J., Schiff, S.L., Brown, S.J., and Sudicky, E.A., Estimating cumulative wastewater treatment plant discharge influences on acesulfame and *Escherichia coli* in a highly impacted watershed with a fully-integrated modelling approach, 647–662, Copyright (2019), with permission from Elsevier.

anthropogenic changes to the “hydrologic regime”. The potential use of a hydrologic response model for understanding hydrology, in general, and runoff processes, in particular, were cited. It is abundantly clear that the original paper was concerned with hydraulics and flow. As we look to the future, linking groundwater with soils, surface water, ecosystems and climate science – in catchments, and across the globe – are exciting and foreseeable challenges. A whole world of new disciplinary, interdisciplinary and transdisciplinary problems is in sight. Contamination of water resources, reactive transport processes and the impacts of hydrologic and water quality changes on sensitive ecological receptors belong on a very long list of contemporary, pressing issues for modern-day hydrology. It is therefore clear that the Blueprint will and must evolve with time – reflecting new scientific advances as well as important and emerging water resources management and policy challenges.

Several papers (e.g., Maxwell et al. (2014); Wu et al. (2015); Tian et al. (2015); Paniconi and Putti (2015)) have described the use and application of integrated models to study water resources, environmental and interdisciplinary problems. It is clear that the 21st century Blueprint is already being realised. Integrated hydrologic models are being developed and applied to study the water quality in watersheds (Fonseca et al., 2014; Hwang et al., 2019), the impact of climate change on hydrologic systems (Erler et al., 2019; Surfleet and Tullos, 2013; Sulis et al., 2011b), the groundwater–land surface–atmosphere connection (Maxwell et al., 2007), links between land use, vegetation and hydrologic systems (Schilling et al., 2014; Banks et al., 2011), coupling streambed hydraulic properties and surface water – groundwater interactions (Simpson and Meixner, 2012) and regional scale water resources management (Wu et al., 2015; Tian et al., 2015; Hassanzadeh et al., 2014; Mazzega et al., 2014). For example, Wu et al. (2015) used a surrogate-based approach with integrated surface water-groundwater modelling for optimizing water resources management in a large river basin. Surrogate models and model emulation can be particularly important when the computational burden is prohibitive, especially when many simulations must be run as a part of an optimisation or uncertainty analysis. Wu et al. (2015) conclude that surrogate-based approaches show promise for bridging the gap between complex environmental modelling and real-world management decision-making.

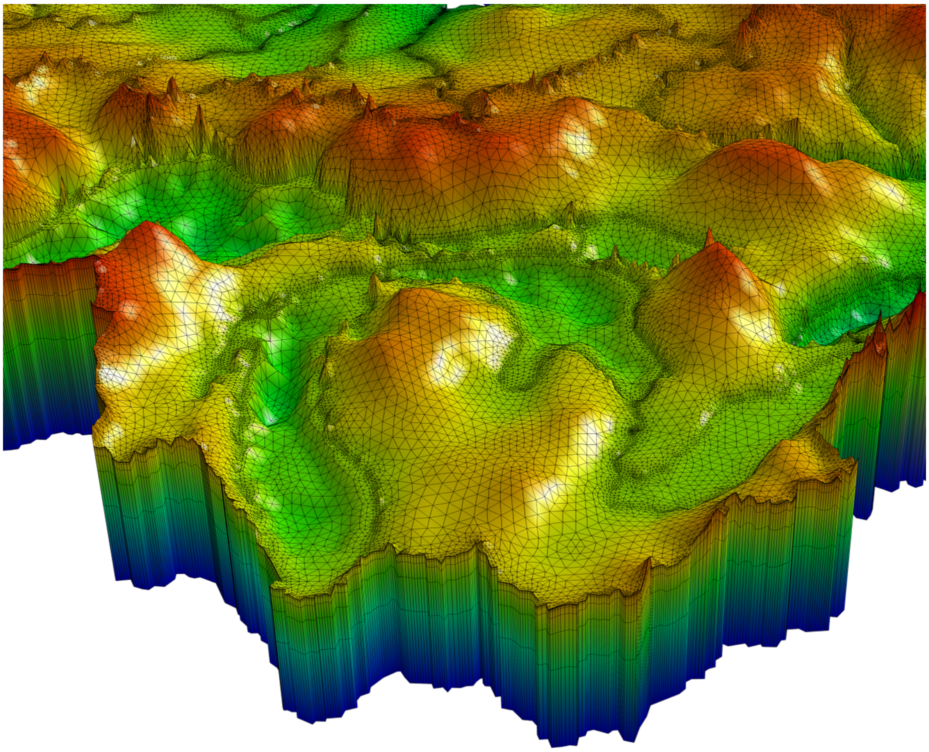

Fig. 9. The HydroGeoSphere 3D triangular prism grid along the Great Lakes region. Hot colors represent high elevations and cold colors show the low elevations. The irregular mesh is refined at the lake shore and along major rivers (Fig. 3 from Chen et al. (2019)). Reprinted from *Canadian Water Resources Journal*, Chen, J., Sudicky, E. A., Davison, J. H., Frey, S. K., Park, Y.-J., Hwang, H.-T., Erler, A. R., Berg, S. J., Callaghan, M. V., Miller, K., Ross, M., and Peltier, W.R., Towards a Climate-Driven Simulation of Coupled Surface-Subsurface Hydrology at the Continental Scale: A Canadian Example, 2019, Taylor & Francis Ltd, reprinted by permission of the publisher (http://www.tandfonline.com).

New social, economic and environmental problems, questions and issues will continue to drive changes in integrated hydrologic science and modelling. Whilst some of these drivers can be anticipated many are currently and inevitably unforeseeable.

5. Epilogue

The Freeze and Harlan (1969) *Blueprint for a physically-based, digitally-simulated hydrologic response model* set firm and exciting foundations for some important developments in hydrologic science that occurred over the last 50 years. Our paper commemorates the 50th anniversary of this seminal paper. We honour and remember Allan Freeze and Dick Harlan and thank them for their insights and wisdom and for conceiving their Blueprint paper.

We traced the story of the Blueprint paper from its earliest origins as it was developed in informal conversation between two friends who shared both an interest in hydrology and a car ride to work; to its update, development and application in proceeding decades; to the birth of the computer codes that ultimately realised the physically-based, digitally-simulated hydrologic response model; and which made Freeze and Harlan's dream a reality within some 40 years of the publication of the original paper. Freeze and Harlan's contribution is quite extraordinary given the state of hydrology in the 1960 s as well as both the limited computational power and limited data available then. One can imagine two friends toying with an idea in the car on the way to work, imagining what advances in computing over forthcoming decades may make possible for hydrologic modelling.

There are many challenges and opportunities that remain. From working with big data and data assimilation as new and ever-increasing datasets come into being; to advances in high-performance computing that will enable us to address new and exciting real-world problems and continue to explore fundamental scientific phenomena and processes; to new interdisciplinary and transdisciplinary problems that bring different, often disparate areas, of science and modelling together. The opportunities and need for groundwater hydrologists, surface water hydrologists, soil physicists, climatologists, ecologists – amongst others – to work together and collaborate to solve a plethora of interesting, important, exciting and emerging problems have never been greater. As Freeze observed in communications with us, getting different hydrologists talking and working together was a main contribution and motivation of the original Blueprint. Today, we can add to the list of disciplines contributing to the much needed interdisciplinary effort. Water quality, ecology, ecotoxicology and climate science are critically among the growing mix.

The future of groundwater science and groundwater modelling, as part of a broader hydrological, geological and environmental enterprise, will depend on advancing and resolving many exciting challenges. The future of groundwater science and groundwater modelling will depend on advancing the Blueprint in both conceptual and implementation terms. As Allan Freeze remarked in communication with us, "Certainly our paper was very much a first pass, and really just an idea piece." It has set the stage for the next generation of blueprints, scientific advances and management applications. It has triggered important scientific discussion and debate.

Today it is abundantly clear that we stand on the shoulders of giants. In 2019, the 50th Anniversary of the Blueprint paper, we celebrate and commemorate the Blueprint paper, its authors Allan Freeze and Dick Harlan for conceiving the Blueprint, and all of the people (too many to name) who have been central to this story over the last 50 years and instrumental in its uptake – from code developers, to model users, to researchers and practitioners – who have refined, advanced, developed, implemented and applied the Blueprint. We look forward with great interest to the next 50 years and to watching how the Blueprint, this field of science and its allied problems and applications continue to evolve. We surmise the prognosis for the future adaptation, evolution and application of the Freeze and Harlan Blueprint is promising. Not bad for a first pass and idea piece.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

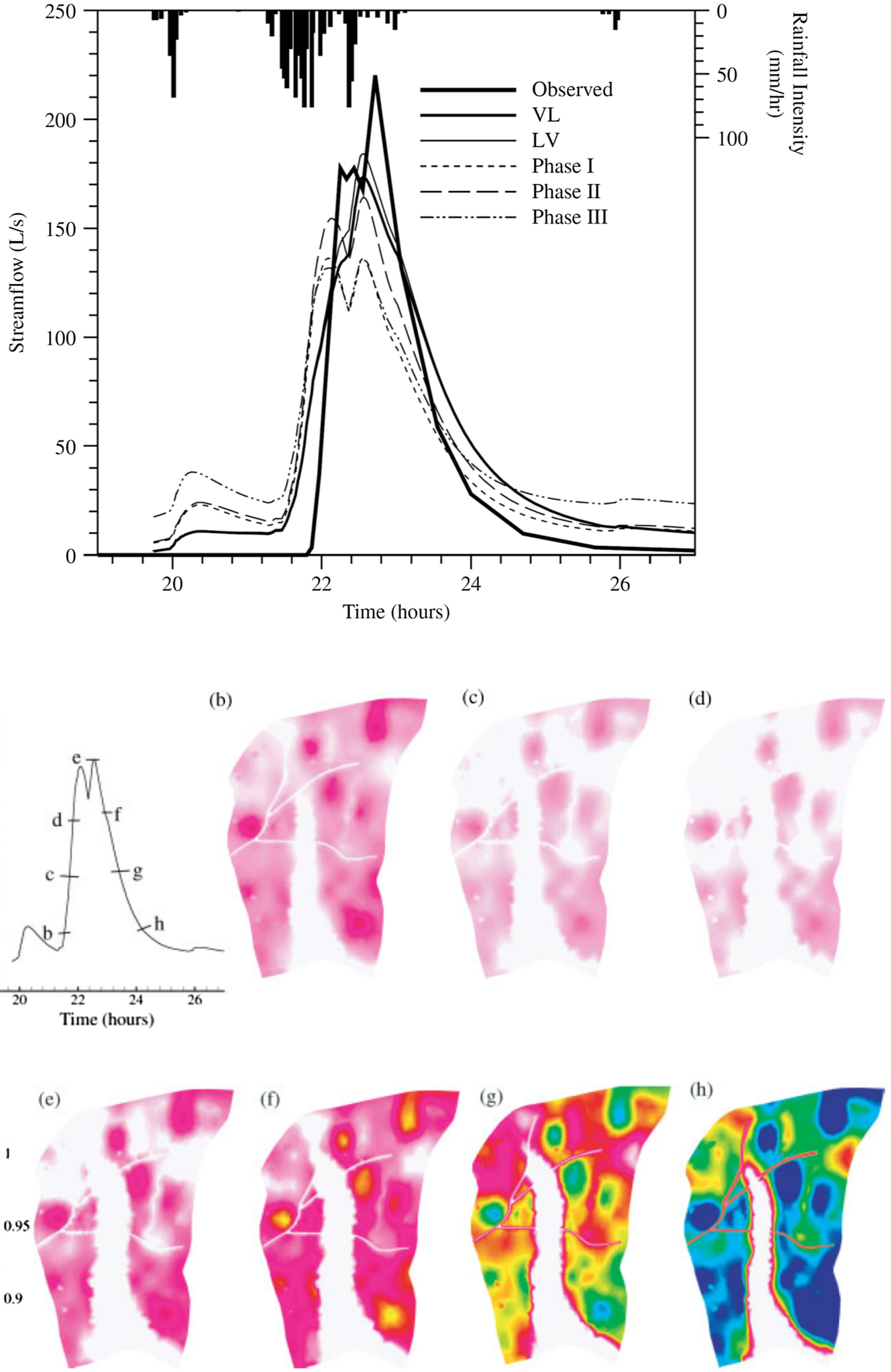

Fig. 10. Top: Observed hydrograph and hyetograph for R-5 event 68 with five InHM simulated hydrographs. The VL simulation is based on VanderKwaak and Loague (2001). The LV simulation is based on Loague and VanderKwaak (2002). The Phase I, Phase II, and Phase III simulations are from Part A of Loague et al. (2005). Each hydrograph was estimated at the weir. Bottom: InHM simulation results for R-5 event 68. (a) Phase III hydrograph (at the weir) showing the b, c, d, e, f, g, h estimation times for the seven snapshots of the surface soil-water content shown in (b)–(h) respectively (Fig. 3 and Fig. 5 from Loague et al. (2005)). Reprinted from *Hydrological Processes*, 19(7), Loague, K., Heppner, C.S., Abrams, R.H., Carr, A.E., VanderKwaak, J.E., and Ebel, B.A., Further testing of the Integrated Hydrology Model (InHM): Event-based simulations for a small rangeland catchment located near Chickasha, Oklahoma, 1373–1398, Copyright © 2004 John Wiley & Sons, Ltd., with permission from John Wiley and Sons.

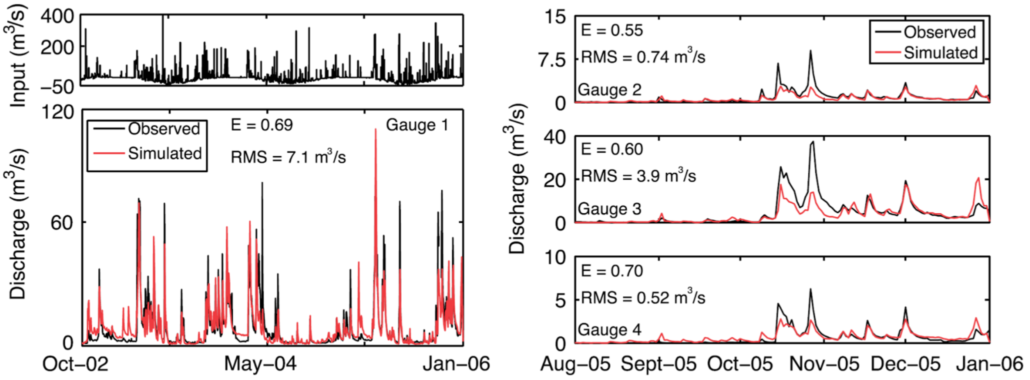

Fig. 11. Observed (black line) and simulated (red line) discharge at the four streamflow gauges in the des Anglais catchment, Quebec, for the verification period. The simulations were performed using the CATHY model (Fig. 4 from Sulis et al. (2011a)). Reprinted from *Hydrological Processes*, 25, Sulis, M., Paniconi, C., and Camporese, M., Impact of grid resolution on the integrated and distributed response of a coupled surface–subsurface hydrological model for the des Anglais catchment, 1853–1865, Copyright © 2010 John Wiley & Sons, Ltd., with permission from John Wiley and Sons.

Acknowledgments

We remember and thank Allan Freeze and Dick Harlan, the authors of the original Blueprint paper. The authors truly appreciate Allan Freeze's time, advice and important contributions to this manuscript. We are grateful for Allan's generosity to help make this paper possible. We were grateful to hear Allan's story firsthand and to have the opportunity to reminisce with him about the historical Freeze and Harlan parts of this paper. The historical perspective is important to document for future generations. Allan's involvement was crucial for ensuring that the historical parts of the story are faithfully reported. We thank the Editor-in-Chief at *Journal of Hydrology*, Professor Geoff Syme, for supporting us to pursue this idea for a commemorative paper. We thank Steve Berg for his assistance in preparing citation data for the paper. We thank Mary Anderson, Keith Beven and Ghislain de Marsily for their most helpful reviews of our paper.

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