
Applicability and methodology of determining sustainable yield in groundwater systems

Frans R. P. Kalf · Donald R. Woolley

Abstract There is currently a need for a review of the definition and methodology of determining sustainable yield. The reasons are: (1) current definitions and concepts are ambiguous and non-physically based so cannot be used for quantitative application, (2) there is a need to eliminate varying interpretations and misinterpretations and provide a sound basis for application, (3) the notion that all groundwater systems either are or can be made to be sustainable is invalid, (4) often there are an excessive number of factors bound up in the definition that are not easily quantifiable, (5) there is often confusion between production facility optimal yield and basin sustainable yield, (6) in many semi-arid and arid environments groundwater systems cannot be sensibly developed using a sustained yield policy particularly where ecological constraints are applied. Derivation of sustainable yield using conservation of mass principles leads to expressions for basin sustainable, partial (non-sustainable) mining and total (non-sustainable) mining yields that can be readily determined using numerical modelling methods and selected on the basis of applied constraints. For some cases there has to be recognition that the groundwater resource *is not* renewable and its use cannot therefore be sustainable. In these cases, its destiny should be the best equitable use.

It should be noted that this example is not to imply that this is a universal mode of behaviour since it assumes capture and interception occur at about the same time. It is used to illustrate the general principles without introducing additional complexity and the need to cover all possibilities that would include where either capture or interception is dominant and initiated at different times.

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F. R. P. Kalf (✉)
Kalf and Associates Pty Ltd,
52 York Terrace, Bilgola, NSW 2107, Australia
e-mail: frkalf@aol.com
Tel.: +61-2-9918-7478
Fax: +61-2-9918-2667

D. R. Woolley
Consultant Hydrogeologist,
3 Barwon Avenue, Turrumurra, NSW 2074, Australia

Résumé Il y a en ce moment un besoin de révision de la définition et de la méthodologie pour déterminer le débit spécifique durable. Les raisons sont les suivantes : (1) la définition courante et les concepts sont ambigus et ne sont pas justifiés physiquement – ils ne peuvent donc pas être utilisés dans des applications quantitatives, (2) il y a un besoin d'éliminer les diverses interprétations et mauvaises interprétations et d'apporter une bonne base applicable (3) la notion clamant que tous les systèmes d'eau souterraine sont ou peuvent devenir durable est invalide (4) souvent il y a un nombre de facteurs excessif qui se rejoignent dans la définition, et qui ne sont pas toujours quantifiables (5) il y a souvent confusion entre le débit durable et optimal et le débit spécifique durable (6) dans de nombreux environnements arides et semi-arides, les systèmes d'eau souterraine ne peuvent être sensiblement développés selon une politique de développement durable particulière où les contraintes écologiques sont appliquées. La dérivation du débit spécifique en utilisant le principe de la conservation des masses mène à l'expression de développement durable de bassin-versant, développement « minier » (mining) partiel (non durable), et développement minier total de l'exploitation (non durable) qui peut être déterminé en utilisant des méthodes numériques de modélisation, sélectionnées en fonction de contraintes appliquées. Dans certains cas il faut reconnaître que la ressource en eau souterraine n'est pas renouvelable et que son utilisation ne peut donc pas être durable. Dans ces cas ses destinées seraient la meilleure utilisation équitable.

Resumen Existe actualmente necesidad de revisar la definición y metodología para determinar lo que significa producción sostenible. Las razones son: (1) los conceptos y definiciones actuales son ambiguos y sin base física de modo que no pueden usarse para aplicación cuantitativa, (2) existe necesidad de eliminar interpretaciones variables y mal interpretaciones y aportar bases sanas para aplicación, (3) la noción de que todos los sistemas de aguas subterráneas son o pueden ser sostenibles no es válida, (4) frecuentemente existen un número excesivo de factores ligados a la definición de producción sostenible los cuales no son fáciles de cuantificar, (5) frecuentemente existe confusión entre la producción óptima de un establecimiento y la producción sostenible de una cuenca, (6) en muchos ambientes áridos a semi-áridos los sistemas de

aguas subterráneas no pueden desarrollarse sensiblemente en base a una política de producción sostenible particularmente donde se aplican restricciones ecológicas. La derivación de producción sostenible utilizando principios de conservación de masa conduce a expresiones para producciones sostenibles en cuenca, minado parcial (no sostenible) y total (no sostenible) que pueden determinarse fácilmente utilizando métodos de modelos numéricos y seleccionados en base a restricciones aplicadas. En algunos casos tiene que reconocerse que el recurso de agua subterránea no es renovable y que por lo tanto su uso no puede ser sostenible. En estos casos su destino debe de ser el uso más equitativo.

Keywords Groundwater · Conjunctive use · Sustainable yield · Water budget · Recharge

Introduction

Groundwater management in many countries has progressed over the second half of the last century from virtually nil to a more regulatory regime today. The change was concurrent with a change in emphasis from resource exploration to resource management, and an increase in the ratio of groundwater usage to groundwater availability. The volume of groundwater authorised for withdrawal has risen to the extent that many important aquifers have been deemed to exceed the “capacity” of the aquifer system to deliver, often described as “over-exploitation” (Custodio 2002). While the actual abstraction is mostly significantly less than the authorised amount, there are cases where it has been assessed that this abstraction exceeds the long-term capacity of the aquifer. In Australia, for example, of the 538 Groundwater Management Units nationwide examined during a national water audit in 2000, 57 are regarded as being pumped at a rate that exceeds their long-term capacity (Australian Natural Resources Atlas – http://audit.deh.gov.au/ANRA/atlas_home.cfm). Water resource managers have sought to redeem the situation by reducing the volume allocated, and in some cases the volume pumped, to a level that they have assessed is “sustainable.”

This action has resulted in a vigorous debate about the way in which the “capacity” of an aquifer to deliver water in a sustainable way should be defined and determined. The two prominent concepts developed to describe this are Safe Yield and, much later, Sustainable Yield. These latter concepts together with a variety of applied constraints constitute what has been called “sustainable groundwater development” (Hiscock et al. 2002). If the concept of sustainable groundwater development is to be applied, then it is essential that both safe yield and sustainable yield be understood. Unfortunately, this is currently not the case and there is a variety of interpretations and often also confusion as to their exact meaning.

This paper re-examines the concept of sustainable yield. It seeks to provide a suitable working methodology

in a basin-wide or groundwater entity context, rather than a specific word definition, and an explanation for practitioners and water resource managers for use in defining groundwater systems under development conditions. Another objective is to return the concept to a sound foundation using fundamental groundwater flow principles. Most of the concepts outlined in this paper are not new. The intention here is to re-examine them from a new perspective as a way of reminding water resource managers and others that fundamental principles should not be overlooked as they seek to show that use of natural resources is sustainable. New generations of practitioners in groundwater and related fields need a reminder of these principles, especially if they do not have a solid background in hydrogeology.

The paper begins by referring to the long historical development of these yield definitions, to place their meaning into context, provide some examples of concepts used in a number of countries, and to outline some of the ambiguities of sustainable yield definitions in Australia. This is followed by a derivation of basin sustainable yield based on conservation of mass principles and applied constraints, and a discussion of the implications of some practical issues. Some examples of sustainable and non-sustainable yield assessment are followed by a listing of some considerations relevant to groundwater management and concepts presented, and conclusions.

Yield concepts and definitions

The progression of the concept of safe or sustainable yield is illustrated in Table 1 (see Appendix), which is a summarised listing in chronological order of the key authors with their yield concepts, definitions and comments. Use of some type of water budget approach is now common in many countries. Table 2, also shown in the Appendix, indicates the approach to groundwater management adopted in several parts of the world. It is based on a summary provided by Evans et al. (2003), some additional references as indicated, and personal knowledge. The table is not exhaustive but illustrates that even in developed countries the approaches may be basic and use simplified and/or ambiguous concepts.

An issue arising from the definitions in Tables 1 and 2 is that there is an ambiguity in the use of the word “recharge.” In some definitions of Safe Yield it is specifically stated that recharge means “natural recharge,” and is equal to natural discharge. Definitions of “sustainable yield” however, may imply that “recharge” includes induced recharge resultant upon changed conditions caused by the groundwater pumping. Induced recharge from stream depletion is the most important of the possibilities. Successful water management clearly depends on *joint* management of surface water and groundwater resources.

It is worthwhile to examine the Australian situation in a little more detail to illustrate the current ambiguities. In doing so readers may find some common threads and ideas that may apply to their own situation.

Table 1 Author, yield concepts, definition and comments

Author	Concepts and definition	Comments
Lee (1915)	Safe yield: <i>“The limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve.”</i>	Hydrologically based on something less than dangerous storage depletion. What does dangerous and regular mean? Yield available in perpetuity (i.e. sustainable)
Meinzer (1920)	Safe yield: <i>“...the practicable rate of withdrawing water from it (the aquifer) primarily for human use.”</i>	Hydrologically based and a yield available in perpetuity (i.e. sustainable). <i>“Sensible, but overdraft not evident until after it has occurred”</i> (Kazmann 1988)
Meinzer (1923)	Safe yield: <i>“The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to the extent that withdrawal at this rate is no longer economically feasible.”</i>	Hydrologically based but dependent on the pumping economics
Theis (1940)	Perennial safe yield: [for non-artesian aquifers that are small and most artesian aquifers] <i>“there is a perennial safe yield equivalent to the amount of rejected recharge [induced recharge] and natural discharge it is feasible to utilize.”</i>	Implies concept may not apply to large aquifer with low diffusivity (T/S) ^a and isolated abstraction
Stuart (1945)	Safe yield: <i>“is the maximum rate at which water may be withdrawn without impairing the quantity and quality of the supply.”</i>	Hydrologically based on the Meinzer concept with water quality constraint added
Conkling (1946)	Safe yield: <i>“Taken over 1 year should not: (1) Exceed average annual recharge; (2) Lower water table so that the permissible cost of pumping is exceeded;(3) Lower water table so as to permit intrusion of undesirable quality.”</i>	Hydrologically based on natural recharge but production facility economics included in definition plus water quality constraint
Williams and Lohman (1949)	Perennial yield: <i>“has been regarded as the maximum rate at which water can be salvaged from the natural discharge, or added to the (natural) recharge or both... In some reports economical pumping lift has been a factor in this definition; however, the economics of recovery seem to be irrelevant to the determination of the quantity of water which an aquifer will yield and so are not considered here.”</i>	Return to a hydrologically based definition. However, no consideration of storage capacity
Thomas (1951, 1955)	Safe yield: suggests abandoning the term because of its indefiniteness	US Geological Survey calls for abandonment of Safe Yield terminology about this time
Synder (1955)	Overdraft/overdevelopment: 5 types (1) Development overdraft-lowering of water table in areas of natural recharge/discharge; (2, 3) Season or cyclic overdraft: zero net change in water levels over specific time period year to year; Cyclic, water levels over two or more seasons and then return; (4) Long-run overdraft: perennial pumping exceeding replenishment (i.e. mining); (5) Critical overdraft-pumping leads to irreversible undesirable result	Definition of overdraft or overdevelopment in areas exceeding sustained (sic) yield (Domenico 1972). All overdraft yields are unsustainable
Kazmann (1956)	Safe yield: – suggests abandoning the term because of its indefiniteness	
Todd (1959)	Safe yield: <i>“the amount of water which can withdrawn from (a groundwater basin) annually without producing an undesirable result.”</i>	<i>“Compact, but adds nothing to clarify the situation in that the ‘undesirable results’ include concern for available water, economics of pumping, quality and water rights.”</i> (Domenico 1972)
ASCE (1961) ^b	Four concepts of safe yield; (1) <i>Maximum sustained (sic) yield— maximum perennial abstraction;</i> (2) <i>Permissive sustained yield— maximum perennial abstraction legally and economically for beneficial use without undesirable result;</i> (3) <i>Maximum mining yield —total volume in storage that can be extracted and utilized;</i> (4) <i>Permissive mining yield—maximum volume in storage that can be extracted for beneficial purposes without undesired result.</i>	Designed to remove ambiguity of safe yield concept. Definition is a mix between basin mass balance (water budget) and production facility response
Freeze (1971); Freeze and Cherry 1979)	Demonstrates relationship between basin water balances using 3D variably saturated model. Simulation defines the <i>“Maximum stable basin yield.”</i>	Illustrated variation of inflows and outflows and storage depletion over time
ASCE (1972)	Two types: (1) <i>Maximum mining yield—abstraction exceeds annual replenishment,</i> (2) <i>Perennial yield—rate at which water can be salvaged from the natural discharge, or added to the [natural] recharge or both.</i>	(1) Exceeds natural plus induced recharge -unique value (2) based on changing values depending on groundwater levels in basin
Domenico (1972)	<i>“The question whether groundwater should be managed on a sustained or mining-yield basis is not yet fully resolved and is controlled by local conditions and demands than by policy decisions in advance of their absolute necessity. This is understandable in that there is likely to be little public sympathy for an announced depletion policy, whereas one of sustained use lends a ring of permanency. Whatever the merits of sustained and mining yield concepts, they are definitely ingrained in groundwater management.”</i>	Page 80

Table 1 (continued)

Author	Concepts and definition	Comments
Bouwer (1978)	Safe yield: Three types. (1) (<i>Normal</i>) Safe yield—is equal to the average replenishment rate of the aquifer.-limited by intrusion near coast; (2) Economic safe yield—rate at which groundwater can be withdrawn without danger of wells drying up before adequate tax base for more expensive water is established (i.e. mining); (3) Legal safe yield—“rate at which a well owner can pump groundwater without getting involved in legal action.”	Mixes hydrological based recharge, production facility maximum available drawdown and non-hydrological legal issues
Bredehoeft et al. (1982, 1997, 2002)	Sustainable groundwater development is determined by capture of natural discharge. Basing groundwater development sustainability on natural recharge (i.e. safe yield) is a myth and irrelevant	Focus is on production facility transient phase leading up to equilibrium. Implies sustainability means groundwater system must reach equilibrium. Numerical modelling required to determine response
Brudtland (1987)	Sustainable development to take into account environmental and social issues and long-term protection of resource	Not specifically related to groundwater but the origin of sustainability concept
Sophocleous (1997, 1998, 2000)	Sustainable yield primarily derived from groundwater storage but ultimately from induced recharge (i.e. surface water depletion). Sustainable yield must allow for sustainability of environment and therefore should be less than safe yield	States that numerical models are best to determine and distinguish between natural and induced recharge. Indicates “irrelevance” of natural recharge ^c
Alley and Leake (2004)	Review differences between safe yield and sustainability	No definition or methodology given but indicate ambiguities and complexities of concepts and usefulness of numerical models in determination

^a Diffusivity T/S: Transmissivity divided by storativity

^b American Society of Civil Engineers

^c Bredehoeft (2002) and Kendy (2003) have also stated that natural recharge is irrelevant

The ARMCANZ (1997) paper notes, “*there is no single understanding or definition of sustainable yield across Australia.*” Government and, in general, community perceptions of appropriate usage of groundwater currently appear to be along the lines that groundwater dependent ecosystems should not be impacted by groundwater pumpage, and that current usage should not be at a rate that would jeopardise its availability for future generations. Consequently, a large part of the debate is about the meaning to be assigned to the term “sustainability” and how to conceptualise sustainable use of groundwater.

An interstate working group has been attempting to derive a definition for sustainable yield that would be acceptable to all States and thus provide a degree of consistency in assessment of sustainable groundwater use across the country. The definition proposed was, “*The groundwater abstraction regime, measured over a specified time frame, that allows acceptable levels of stress and protects the higher value uses that have a dependency on the water.*” (Evans and Cook 2002).

This definition was not universally acceptable, and was subject to suggestions that it may be so flexible as to be of little use. For example, reference to sustainable yield for a specified time frame implies that a time frame of decades is acceptable, in which case the term sustainable loses its meaning (*sustain*—enable to last out, keep from failing: Concise Oxford Dictionary). The term is being used as an aid to the understanding of groundwater systems by non-hydrogeologists preparing water-use plans, and its definition must therefore be clear and unambiguous. A groundwater withdrawal regime that is sustainable for 30 years, for instance, may lead to failure

in year 31. That does not mean that the particular abstraction regime should not be adopted, but the possibility that this might occur must be accepted (or at least realised) by all users of groundwater.

A second area of ambiguity of the above definition of sustainable yield is the reference to “higher value uses.” A higher value use may in fact be withdrawal for irrigation or other consumptive use. Application of the initially proposed definition would not, then, ensure the protection of groundwater dependent ecosystems or the availability of the resource for future generations, despite the implications apparent from an initial reading. Both are in fact dependent on the way the definition is interpreted.

The Australian National Groundwater Committee finally adopted a slightly modified version namely: “*The groundwater extraction regime measured over a specified planning time frame that allows acceptable levels of stress and protects dependent economic, social and environmental values.*” The definition was released subject to the proviso that it should be read in conjunction with a series of qualifications that occupies two pages. The qualifications recognised that the total extraction volume is not necessarily the most important part of a groundwater management regime, that some level of stress on the aquifer will occur, that there may be some storage depletion, and highlighted the need for trade-offs between these aspects. Whilst this definition is an improvement, the meaning is still open to various interpretations. The definition itself is still subject to decisions on what levels of stress are acceptable. In New South Wales, for example, where the definition has been adopted with the provisos, a default allowance of 30% of the long-term average annual net recharge (i.e. including induced re-

Table 2 Some examples of current water budget approaches

Country/state	Water budget approach	Comments
Britain	Total abstraction, plus the required stream flow, must be less than recharge	Indirect limit applied to groundwater abstraction by community decisions on stream water quality. (Abstraction leads to loss of stream flow and possible degradation of quality.)
India	Safe yield policy depending on a given percentage of rainfall. Target is to have abstraction less than recharge	Recharge rate for various aquifers is specified as a percentage of rainfall in Central Government publications. Calculations and administration by States. Inconsistently applied. May improve with implementation of recent
China	New legislation is based on a safe yield policy	legislation Aim is to reduce abstraction where it exceeds recharge, and to prevent increased abstraction where it balances recharge
Kansas, USA	Groundwater Management Districts (GMD) in east and northwest now have a safe yield policy, but introduced too late to prevent water level declines. Western GMDs have a planned depletion policy	Widespread falls in groundwater level of significant magnitude. Non-recoverable in large areas
Arizona, USA	Over-use and falling water levels addressed by legislation that mandates safe yield (balancing abstraction with recharge)	Not clear that targets will be met
California, USA	Courts have determined “equitable distribution” over large areas	May not lead to sustainable use. San Gabriel has defined “natural safe yield” (quantity that can be extracted from long-term average annual supply) and “operating safe yield” (quantity determined by agency for use in a particular fiscal year)
Rhode Island, USA	Safe yield policy	Uses the Todd (1959) definition (see Table 1)
Indonesia	Implied target of reducing abstraction to less than recharge	Sub-optimal location of abstraction facilities has led to operational problems
Arabian Peninsula (Algeria, Oman, UAE, Syria, Jordan, Bahrain, Qatar, Kuwait, Saudi Arabia)	No specific yield policy. Abstraction is without volume limitation for individuals	Range of groundwater withdrawal as percentage of renewal 110 to 1,456% Young (2002)
Mexico (Guanajuato State)	No specific yield policy. Efforts to set up groundwater management program	Sandoval (2004)
Western Turkey	Safe yield policy since 1960's. Now exploring groundwater development using various yield policies	Sakiyan and Yazicigil (2004)
Australia	Sustainable yield policy, based on keeping abstraction less than natural recharge, with specific allowance for groundwater dependent ecosystems (including rivers)	Use of time frame in definition of sustainable yield allows for some groundwater mining to be referred to as sustainable

charge) is provided for groundwater dependent ecosystems (DIPNR 2002). Despite these inadequate definitions, many water authorities in Australia are using numerical models or water balance methods for water resource assessment. Uncertainty remains, however, on how to precisely determine sustainable yield, and link it to the concept of sustainable development. This also appears to be the case in other parts of the world.

Need for a review of the sustainable yield concept

An assessment of the amount of water that a community should draw from an aquifer or basin depends on many factors, and they are not always of equal weight. For example, one problem that arises in using the sustainable yield concept is in a groundwater system with virtually no recharge from any source either under natural conditions or following development. Under these conditions, use of

the term *sustainable* is questionable given that use of groundwater in these circumstances would be essentially a mining venture. Using an analogy, what for example would be the sustainable yield or development of mineral resources such as coal or iron deposits? Clearly the term is meaningless in this context. These resources have a finite lifetime, dependent on the rate of abstraction.

It is also unfortunate that sustainable yield is often seen to be limited to, or a rate somewhat less, than the rate of natural recharge to aquifer systems (sometimes called “safe yield”). Using such a definition restricts much of the beneficial use of the aquifer system as a conveyor and storage medium for the total water resource. Induced stream flow into an aquifer that might otherwise be lost by surface evaporation is an example of such a benefit.

A requirement for ecologically sustainable yields provides a further constraint on consumptive groundwater

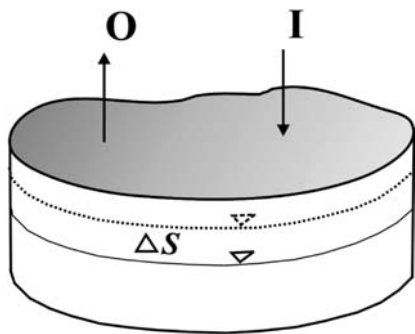


Fig. 1 Flow mass balance

use and also presents a formidable challenge to groundwater managers on how to define this yield.

There is clearly a need for a return to a more basic and practical definition and understanding of the concept of sustainable yield, so that groundwater managers and users are aware of the implications of withdrawal decisions that they are making, and are not misled about the long-term impacts of groundwater pumping regimes.

Sustainable yield concepts and methodology

It is clear from the previous discussion that any methodology to determine sustainable yield and thus sustainable development should try to accommodate the following:

1. Definition or methodology to be based on sound hydrological and groundwater flow principles (i.e. law of conservation of mass) so as to remove ambiguity of meaning and allow determination of quantitative output.
2. Sustainable yield must enable the groundwater system to reach a new state of equilibrium in time.
3. Allow numerical models (and modellers) to provide the quantitative output such as basin mass balance (water budget) in assessing sustainability and also, if required, production facility “performance” or well field optimal yield and drawdown.
4. Allow a particular sustainable yield (or non-sustainable yield) derived from such models to be selected based on or constrained by other criteria (i.e. water authority ground and surface water usage limits, community needs, legal factors, economic issues, ecological requirements, water quality, effects of subsidence).

To achieve these goals it is important first to differentiate and separate the sustainability of a basin aquifer system and the “performance” of the production facility abstracting groundwater. The definition of sustainability herein refers (and in our opinion should refer) to the former and not the latter. To this end, the sustainable yield can be derived from conservation of mass principles in a groundwater basin or sub-basin as follows:

$$\text{Inflow} - \text{Outflow} = \text{Change in storage}$$

$$I - O = \Delta S/t \quad (1)$$

where I , O are here defined as the total inflow and outflow rates ($L^3 T^{-1}$) from various sources or sinks and ΔS is the storage accretion or depletion volume (L^3) and t is time (T). If the outflow is greater than inflow then some storage is depleted and groundwater level falls, whilst if the inflow is greater than outflow then there is storage accretion and groundwater level rises. If inflow equals outflow then the water levels remain static because there is no gain or loss in storage. Inflows would normally include, for example, rainfall recharge, runoff and stream/lake leakage, whilst outflows would include springs, evapotranspiration, base flow, drains and pumping abstraction¹. Artificial recharge is also a possible inflow component.

Basin sustainable yield

Under long-term natural conditions, with no development, there will be an average inflow I_n and outflow O_n . That is, an average water balance or equilibrium in the basin is achieved. Under development, with increased artificial abstraction (i.e. pumping), outflow can decrease because of “capture.” It is suggested that perhaps a better term would be *interception*² (for example, decreased evapotranspiration, reduced groundwater flowing into springs or streams due to water table lowering)³. Also at a given time, inflow can increase as additional water is induced to flow into the aquifer system because of abstraction drawdown applied to the groundwater system (i.e. leakage from streams/lakes, recharge in former discharge areas). The induced inflow may occur before interception of outflow or vice-versa depending on the position of abstraction area relative to the inflow sources and outflow sinks or they may occur more or less simultaneously. Either or both of these processes will continue for a given time until for a given abstraction rate the new total outflow (which now includes pumping) is balanced by the new total inflow rate. The time taken to attain equilibrium will depend on the magnitude of the abstraction rate,

¹ In administratively defined but geologically unbounded groundwater areas or zones the flows would also include lateral inflow and outflow through the up and down gradients of the aquifer system.

² A suggested distinction is made here between capture and interception. Abstraction could intercept outflow from discharge components (evapotranspiration, springs, potential base flow) since this flow originates from natural aquifer recharge or it could capture natural recharge and stream runoff and baseflow/lake and wetland surface water since these components originate (except baseflow) outside of the groundwater system. The word interception makes a distinction that this refers to taking groundwater flow that originated as natural recharge. (*intercept: to take or seize on the way from one place to another, cut off from the intended destination-Macquarie Dictionary*)

³ Note that abstraction interception of natural outflow means that an equivalent volume of natural inflow (recharge) is eventually captured.

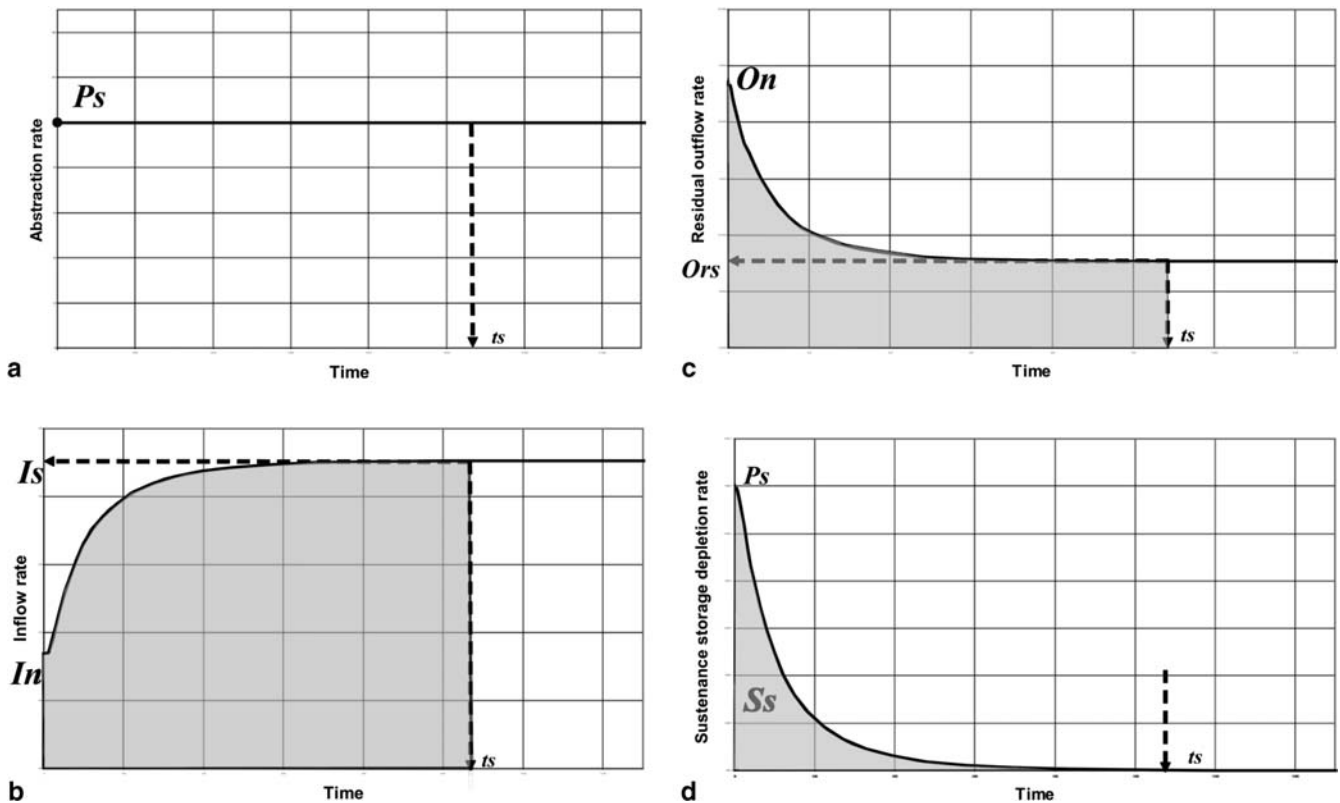


Fig. 2 Water balance components— (a) Abstraction rate; (b) Inflow rate; (c) Residual outflow rate; (d) Sustenance storage depletion rate

aquifer characteristics, and distances to recharge boundaries.

To examine how abstraction will affect the various natural inflow and outflow components of the groundwater basin, assume a system in equilibrium at time zero where the natural inflow is balanced by the natural outflow.

$$In = On \quad (2)$$

If a constant abstraction rate (say pumping)⁴ P_s is introduced to this groundwater system (Fig. 2a) then there will be some aquifer storage depletion as the cone(s) of drawdown depression expand in the aquifer. Assuming that both induced inflow and interception outflow occur simultaneously then after some time this abstraction will cause additional (induced) inflow and interception of some of the natural outflow.

A typical curve for the inflow rate in this case is shown in Fig. 2b that starts at the natural inflow rate I_n and increases until a new equilibrium is established at a new (sustainable) inflow rate I_s at time t_s . Similarly in this case during the same time, pumping abstraction would progressively intercept some of the natural outflow O_n , which will decrease progressively to a value O_{rs} which is the (sustainable) residual outflow (Fig. 2c) at time t_s . The

total outflow rate from the basin at equilibrium time t_s is therefore:

$$Os = Ps + Ors \quad (3)$$

comprising pumping abstraction and the sum of the remaining (residual) components of natural outflow. At this point the new inflow I_s is balanced by the new outflow O_s .

The corresponding storage depletion rate and curve during the same time period is shown in Fig. 2d. This figure shows that the rate of storage depletion decreases in time from an initial value of P_s until it reaches zero at time t_s after which there is no further storage depletion. The storage depleted S_s is the volume depicted by the area under the curve in Fig. 2d. S_s is defined in this paper as the sustenance storage to achieve sustainable equilibrium of inflow and total outflow.

There will be a specific time at which, for a given abstraction, if it is feasible under prevailing production facility constraints, the inflow may reach a basin wide maximum with zero residual outflow. This flow can be defined as the basin maximum sustainable yield⁵ at a time t_d where

$$Id = Pd \quad (4)$$

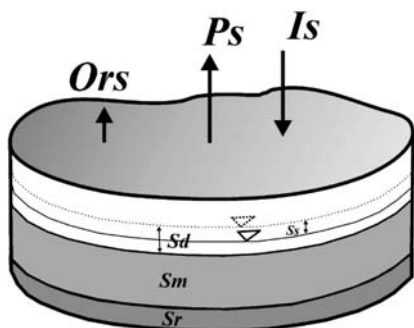
⁴ Where there is a partial return through percolation of pumping for irrigation P_s would represent the net abstraction.

⁵ This is similar to the Maximum Stable Basin Yield (Freeze 1971; Freeze and Cherry 1979).

Table 3 Definition of inflow and outflow components

Conditions	Total inflow rate ¹	Total outflow rate	
	Inflow rate	Outflow rate	Abstraction rate
Natural conditions	$I_n =$	O_n	zero
Basin sustainable yield at time t_s	$I_s =$	$O_{rs} +$	P_s
Basin maximum sustainable yield at time t_d	$I_d =$	zero	P_d

¹ Total inflow may also include artificial recharge under development conditions

**Fig. 3** Sustainable inflow/outflow and storages

Here the new inflow rate I_d is the basin maximum sustainable inflow rate (with zero residual outflow) and P_d is the “basin maximum sustainable yield.” Such a condition, from Eq.(1), will result in static water levels with neither storage accretion nor depletion after time t_d . It is important to note that the basin cannot sustain indefinitely any abstraction rate higher than the basin maximum without drawing on storage over and above that used to achieve this maximum. It is unlikely of course that the basin maximum sustained yield would be desirable since it could mean complete loss of both residual outflow and stream flow depending on the disconnected seepage rates⁶ from the stream channels.

The equilibrium terms and relationships in the foregoing paragraphs are summarised in the following Table 3.

A set of separate storages in the basin as shown in Fig. 3 can now be defined.

Here S_d is the development or maximum sustenance storage depletion required to establish the maximum sustainable yield P_d ; S_m is the available mining or mineable storage and S_r is the unrecoverable storage. The storage volumes shown in Fig. 3 are diagrammatic and in reality would be the spatially integrated volumes over the aquifer system. Thus $S_d =$ Maximum sustenance storage = storage depletion required to establish I_d ; $S_m =$ Mineable or mining storage = recoverable storage remaining after S_d is used; $S_r =$ Unrecoverable storage = storage that cannot be accessed

Total storage under natural conditions at zero time $S = S_d + S_m + S_r$

⁶ Seepage rates that are controlled entirely by stream stage and streambed permeability with water tables (potentiometric surfaces) below the streambed bottom.

It follows of course that in a basin there can be any number of sustainable yields less than the maximum because such yields would be conservative. That is, they would require less inflow and outflow interception than the groundwater system can potentially provide. For these sustainable yields, the sustenance storage S_s (Fig. 3) will vary but is always less than S_d depending on the particular abstraction rate P_s . The sustenance storage S_s is of course equal to S_d when P_s equals P_d .

Fig. 4 (based on Fig. 2d) shows a number of storage depletion rate curves less than the maximum (at an abstraction rate P_d) all of which reach zero and consequently indicate that the total outflow is balanced by inflow and the abstraction is therefore sustainable. P_d represents the basin maximum sustainable yield, P_{s1} , P_{s2} and P_{s3} are examples of basin sustainable yields and P_{pm} represents a basin partial mining yield⁷.

Any yield less than the basin maximum for the same time period would lead the system to equilibrium or steady state conditions at some time t_s less than t_d depending on the outflow rate and therefore abstraction rate (Fig. 4).

The reason of course why there are any number of sustainable storage depletion rates in the case given in Fig. 4 is that increasing abstraction rates can often intercept increasing amounts of natural outflow as well as inducing increasing rates of inflow from surface bodies of water such as streams and lakes⁸.

Definition of sustainable yield volume up to equilibrium

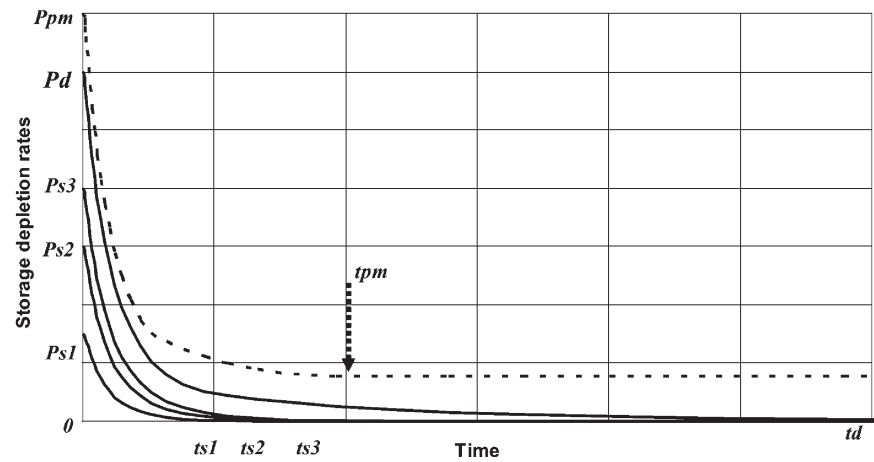
For an abstraction rate P_s it can be shown that the sustainable yield volume prior to equilibrium is given by:

$$Pst_s = \left(\int_0^{t_s} I dt - \int_0^{t_s} Or dt + S_s \right) \quad (5)$$

The inflow and outflow integral terms are required since they include the sum of all inflows and outflows that vary over time (increase and decrease respectively) up to equilibrium time t_s . They represent the corresponding areas under the curves shown in Fig. 2b, c. As noted previously, the sustenance storage S_s used during this time

⁷ Note that P_{pm} , P_d , P_{s3} , P_{s2} , P_{s1} are starting values only on the vertical axis with each curve representing the storage depletion rate that ultimately reaches zero at equilibrium but a constant value for the particular partial mining (non-equilibrium) conditions. For each sustainable rate, the area under each curve is the sustenance storage required to reach equilibrium.

Fig. 4 Sustainable and partial mining yield storage depletion rates



to achieve equilibrium, is represented by the area under the curve shown in Fig. 2d. The sustenance storage should not be considered as a mining storage since this storage can be replenished (provided there is no significant subsidence or severe climatic changes) if abstraction ceases.

Equation (5) above indicates that the abstraction volume up to t_s is equal to the total inflow volume (which includes the natural inflow component), minus the residual outflow volume plus the sustenance storage depletion volume. Beyond equilibrium, the sustainable yield is simply the sustainable inflow rate minus the residual outflow rate. That is, it follows from Eq. (3) for any time period greater than t_s the sustainable yield is given as:

$$P_s = I_s - O_{rs} \quad (6)$$

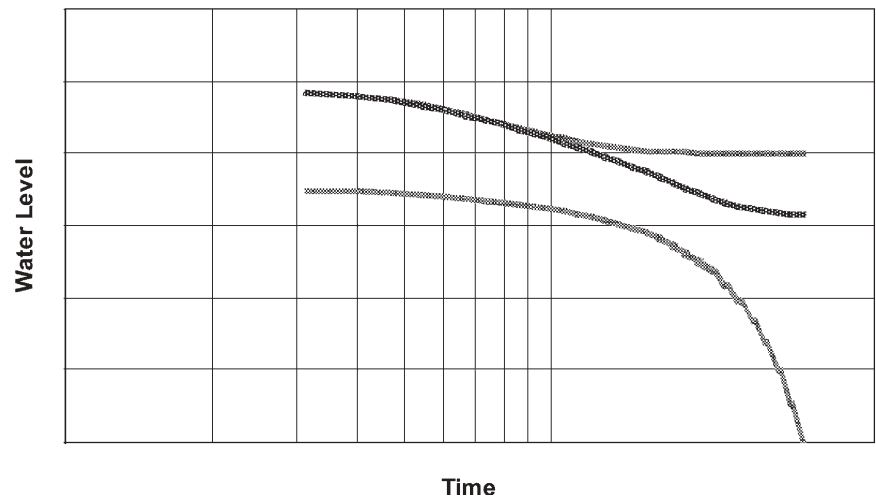
where O_{rs} is the equilibrium residual outflow rate.

Unfortunately, the equations given above cannot be solved directly or easily, and require in most cases, a calibrated numerical model for solution estimation. The equations are a direct expression of the water budget components available from such models. Given that the curves such as displayed in Figs. 2 and 4 are provided as output by numerical model mass balances, using such models provides a direct means of deciding, based on other criteria, which of the possible sustainable yield inflow and outflow curves are permitted for the basins sustainable development; that is, which of the possible curves represents the Permitted Sustainable Yield.

Some corollaries that follow from the above are that:

1. Any withdrawal rate greater than the natural inflow I_n and less than or equal to the maximum sustainable inflow I_d will use part of the maximum sustenance storage S_d (that is S_s), until a new equilibrium is established. There may be time lags in the drawdown reaching either certain recharge or discharge zones or both during development of equilibrium, but this will not violate the equations given above. Expansion of drawdown cones is simply a reflection of use of the sustenance storage S_s over time. The time t_s at which this equilibrium will be reached is a function of the diffusivity of the aquifer system (T/S), and for exam-
2. The abstraction rate can be higher than the maximum sustainable abstraction rate P_d , but only because this higher rate is drawing from the sustenance storage S_d . Ultimately the higher yield would need to be reduced to the maximum abstraction sustainable yield in order to establish equilibrium. If the withdrawal rate is not decreased, it can only be maintained by drawing on the mining storage. For example, Fig. 4 shows a storage depletion rate that starts at an abstraction rate P_{pm} and that for a time will be providing water at a rate that is much higher than the maximum sustainable rate; however, when the sustenance storage is used up mining storage will need to be utilized. This occurs at a time t_{pm} when the depletion rate becomes constant at a rate greater than zero. Any constant storage depletion rate greater than zero means that the inflow and intercepted outflow is insufficient to sustain the abstraction rate. Hence P_{pm} is not sustainable.
3. There is no time frame required to define or determine the basin sustainable yield. Thus use of a time period would only be a convenience for planning purposes in setting a planning horizon and is not fundamental to the principles outlined.
4. An apparent paradox is that it is quite possible for a well field in one part of the basin to go “dry” yet for the basin as a whole to have a number of sustainable yields. This simply demonstrates that the well field

Fig. 5 Model Simulated Draw-down



development is not optimal and that the sustainable development of the groundwater resource must include equitable distribution of abstraction. Individuals or groups cannot selfishly appropriate the groundwater resource. Porous media, unlike dam storage, will not allow it.

Mining (non sustainable) yield

If I_n (the natural inflow rate) is zero or negligible, and therefore O_n is also negligible (assuming a pre-development equilibrium has been reached), for example in a very arid environment where the resource is essentially a fossil remnant, then the system has no basin sustainable yield but only a mineable or mining yield P_m with a maximum time for exhaustion given by:

$$tm = (S_d + S_m)/P_m \quad (7)$$

where S_d is the maximum sustenance storage (which in this case is for all practical purposes zero), S_m the mineable storage and P_m is the abstraction rate.

Thus, in this case, there is no sustainable yield but only a mining yield limited essentially by the available, accessible storage. Setting a time frame for such a yield in the vain hope that it remains “sustainable” or might become sustainable would be invalid.

From a management point of view a mining yield is defined where inflow (natural or induced or both) to the basin and natural outflow is negligible.

Partial mining (non sustainable) yield

Many systems will lie between the two cases described above. Where the abstraction is greater than the difference between the maximum inflow and residual outflow (i.e. as would be implied by Eq. (6) then an additional mining yield O_m is required to maintain the abstraction rate. Thus the partial mining abstraction rate P_{pm} can be defined at

some time t_{pm} (Fig. 4) when the depletion rate becomes constant as:

$$P_{pm} = Id + Om \quad (8)$$

Such a yield cannot be “sustained” indefinitely but only until mining storage S_m is consumed.

Water level response

Water levels alone are ambiguous and cannot be relied upon to determine whether a system yield is sustainable or not. This may be readily seen from three curves shown in Fig. 5 from actual model simulations of a small basin with and without river leakage (upper curves and lower curve respectively) over a given time. The water level logarithmic dimensionless time plot up to time of the first log cycle does not indicate that any of the yields are sustainable over this time period. Although the lower curve has a greater absolute drawdown the rate of drawdown is greater for the two upper curves (generated for two different river bed permeability values) than they are for the lower curve generated for a case with no river leakage. Based on the data up to the end of the first log cycle it might well be concluded that the yields that led to the drawdown rates for the upper curves are unsustainable and that there has been over allocation. The curves after this time reveal, however, that both upper curves are sustainable in the longer term with one yield reaching equilibrium more quickly than the second. The lower curve clearly is representative of unsustainable conditions and is a partial mining yield situation.

The implications of this analysis for water resource managers are particularly important where allocation of both groundwater and surface water are being made to users. Serious double counting may result if groundwater allocations are made separately to surface water allocations on the basis of the early part of the upper curves in Fig. 5. The long-term sustainability of the groundwater withdrawal will be supported by a corresponding lower river flow, which might not be sufficient to provide for

surface water allocations determined on the basis of the original river flow. Again, there is no simple answer on how to resolve this judgement dilemma. A numerical modelling approach combined with experienced assessment would appear to be the best currently available method of trying to resolve it. Models will of course be no more accurate than the data on which they are based and the assumptions made but they can provide insight into the possible range of long-term effects of conditions identified in the field. Where data and interpretation of conditions are uncertain, probabilistic approaches could be of great value in guiding management plans.

Water quality

Water quality will affect the above relationships to the extent that impacts of groundwater withdrawal from an aquifer can include degradation of water quality, which in turn would reduce the abstraction rate. Thus abstraction could be restricted either over time or spatially, depending on water quality issues. For example, returned irrigation water or downward leakage from saline aquifers could lead to poor water quality over a period of time. Salt-water intrusion may also limit abstraction. Prediction of these effects could also be achieved using numerical models where necessary.

Ecological constraints

Ecological requirements will also place restrictions on abstraction. This concept can be accommodated by defining a residual outflow O_{re} greater than O_{rs} , and an inflow I_e less than I_s so that the excess or surplus outflow and additional surface flow are available for environmental purposes. For example, a larger residual outflow means that more groundwater would be available for evapotranspiration, which would be equivalent to maintaining higher water tables beneath areas of phreatophytes. At equilibrium the ecological sustained yield would be given by:

$$P_e = I_e - O_{re} \quad (9)$$

Where P_e is the ecological sustainable yield and I_e is the ecological sustainable inflow.

Storage depletion rate would be represented by a curve shown in Fig. 4 that is lower than the corresponding non-ecological sustainable yield depletion curve.

It is clear that the community and groundwater managers need to understand that such a constraint may prevent the use of some groundwater resources. In drier parts of the world, the ecological sustainable yield and even the non-ecological sustainable yield concept could place it in direct conflict with any significant groundwater use at all.

Practicalities of yield assessment

The above theoretical framework for defining sustainable yield does not consider a number of practical issues and limitations that need to be discussed. These include the application and implications of the principles outlined in moderately large to very large basins and in designated groundwater zones or areas and the variability of climatic events.

Groundwater entity definition

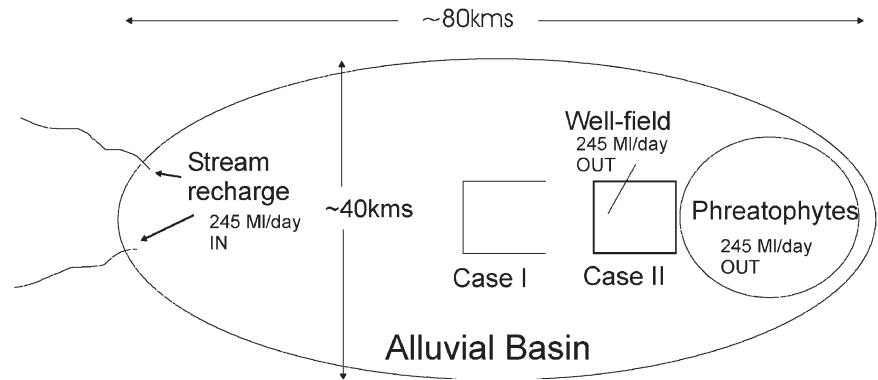
This paper refers consistently to "basin" as the groundwater entity. This was necessary to introduce the concepts discussed. However, in reality, the groundwater entity might be an area or, more precisely, a zone that is partially bounded by geological boundaries, or it could be a designated groundwater zone defined by surficial property boundaries or topographic limits that leave the area geologically unbounded. This means there are no physical barriers of low permeability material that laterally constrain inflow, outflow and drawdown propagation.

In these circumstances, it may be a practical necessity to define a groundwater entity that is unbounded and to determine the sustainability for that zone. This will require an area to be defined in order to limit the drawdown propagation within the designated area boundaries. In a sense, this is the same premise used in numerical modelling studies in defining a working grid so that the model grid boundaries lie outside the range of influence of the proposed stresses. Defining a groundwater entity in this way would also be useful for planning purposes in very large basins. Clearly, defining such a groundwater zone must be a requirement if modelling studies are to be used in estimating the type of yield that is applicable. It is emphasized here that if predicted drawdown is not contained within these boundaries then the "sustainability" assessment would not be valid. Provided predicted drawdown is contained within the area boundaries then the flow principles outlined previously would apply in a similar way.

A groundwater entity defined in this way could also be used in an area or zone where good quality groundwater is wholly or partially surrounded by poorer quality groundwater. In this situation, the poorer quality groundwater zone could be excised from the analysis or modelled area leaving a defined good quality groundwater entity and its boundaries for application of the principles outlined in this paper. This would lead of course to a more conservative yield determination than the case without excise.

It is evident that a determination of whatever type of yield is considered, using a defined groundwater entity may be quite different (and often more conservative) than one determined over a much larger area or region or for a hydrogeologically enclosed basin. However, provided the assumptions are stated, there should be no ambiguity.

Fig. 6 Diagrammatic sketch of the numerical model basin of Bredehoeft et al. (1982), Bredehoeft (2002)



Variability of rainfall and stream recharge events

The vagaries of the climate in drier parts of the world are well known. Rainfall can vary substantially from year to year and rainfall residual mass curve trends can vary markedly over decades or more. This affects the availability of streamflow and other bodies of surface water that would provide natural and induced inflow components to an aquifer system under development. Hence the assumptions of constant inflow (and constant residual outflow) used in the earlier discussion will not strictly apply. However, the variability of inflow (and basin outflow) does not violate the mass conservation principles outlined previously. Also, under normal circumstances, years of lower recharge will be balanced by years of higher recharge and therefore the outcomes discussed will apply on average. Under a constant abstraction regime, some of the “slack” in recharge reduction, depending on the aquifer system, can be taken up by the sustenance storage acting as a buffer. An aquifer system that can be demonstrated to be classed as having a sustainable yield under average conditions should use the storage buffer in this way to “weather through” the recharge reduction until conditions improve. Sustainable assessment has to be based on average conditions, using the longest possible series of historical records.

Nevertheless, extended droughts remain an issue, and it is evident that in many cases sustainable yield could become a partial mining yield unless the abstraction is reduced. Prediction of such climatic events is not feasible at present and therefore there will be uncertainty about “sustainability” of abstraction under these circumstances. Managers should be prepared for such eventualities with action plans at hand for implementation. The best approach is the use of a numerical model, with comprehensive water budget outputs coupled with a probability methodology (e.g. Monte Carlo methods) for determining how the aquifer system may behave in the long term under variable climatic conditions⁸.

⁸ Such analysis could also consider changes in land usage that affect the hydrological water balance.

Examples of sustainable and non-sustainable yield

The Bredehoeft basin

Bredehoeft et al. (1982) and Bredehoeft (1997, 2002) suggest that: (1) “The idea that knowledge of the recharge (by which one generally means the virgin rate of recharge) is important in determining the size of a sustainable development is a myth. This idea has no basis in fact”; (2) “capture from natural discharge is usually what determines the size of a sustainable development”; (3) “Once a new equilibrium is reached, the natural discharge is reduced by an amount equal to development-capture equals development. This statement has nothing to do with recharge.”

A diagrammatic sketch of the example model basin used by them is shown in Fig. 6. The roughly oval shaped alluvial basin is about 80 km by 40 km in size with about 610 m of saturated sediment surrounded by low permeability hard rock. Two streams splay out onto the alluvium and completely lose their flow to the subsurface at one end. The only natural discharge is by phreatophyte evapotranspiration in a broad area at the other end of the basin. There is no recharge by precipitation and no permanent streams that cross the basin land surface. Natural stream recharge is equal to evapotranspiration loss (natural discharge or outflow) under pre-development equilibrium conditions.

A well field with total abstraction equal to stream recharge (100 cubic feet per second, ~245 Megalitres/day) is simulated at two locations in two scenarios shown as Case I and Case II in Fig. 6. Bredehoeft (2002) shows that over time the well field utilizes all of the natural discharge and reaches equilibrium (depending on the transmissivity and well field location) after a period of between 400 and 1000 years. He concludes, “it is the rate at which the phreatophytes consumption can be captured that determines how this system reaches sustainability,” and “that capture always entails the dynamics of the aquifer system.”

Bredehoeft’s conclusions are focused of course on the well field “performance,” that is the production facility response, during the transient phase leading up to steady state flow (to sustainability). The focus is understandable because this transient phase in his particular example of a large basin with a very large storage would span numer-

ous human generations (400 to 1,000 years). However, from a basin mass balance perspective it is quite evident that any further increase in well field discharge would render this yield unsustainable in the very long-term and certainly in a relatively shorter-term if the development were to increase substantially. For example, a ten-fold increase in the number of similar sized well fields pumping at three times the discharge would practically deplete this hypothetical groundwater system completely in less than a human lifetime.

Two points that emerge are that (1) a lack of knowledge of the natural recharge may have led stakeholders in this basin to be unaware that the increased abstraction was unsustainable, and (2) it could have been argued that if the well field had been situated at the recharge end of the basin then it could be said to have captured all of the natural recharge and that this determined the sustainability of the development rather than interception of outflow, although obviously outflow would be influenced⁹.

A determination of natural recharge rate for this basin example would be relevant from a basin mass balance (water budget) perspective since the natural recharge rate, which generated the natural discharge prior to development, determines the maximum sustainable yield of the basin in this example. It also maintains the pumping discharge, independent of where the production facility is located under equilibrium conditions. Once equilibrium is reached, withdrawal from the aquifer would have to be equal to or less than the rate of natural recharge if mining of the resource is to be avoided.

There is agreement with Bredehoeft (2002) to the extent that a determination of natural recharge alone is an oversimplification for determining sustainability and that the use of numerical models should be applied to this task. However, natural recharge is of course relevant in this context otherwise it would not be possible to set up the pre-development steady-state conditions for such models to determine sustainability¹⁰. There is agreement also of course that sustainability implies that the groundwater system will reach equilibrium at some time.

Consider now the case where the same basin is situated in a more humid environment, with a large permanent river meandering across it. Let the well field be in a location remote from the zone of evapotranspiration and near the river in good hydraulic connection with the aquifer. In this case, the production facility response would be controlled largely by the induced recharge, provided of course that this river flow is comprised

dominantly of runoff¹¹. In this case, a determination of natural recharge (and therefore natural discharge) would not be as important (although not irrelevant) in determining either the response of the production facility or the sustainability of the basin groundwater system. Sustainability of the basin groundwater system would be predominantly maintained by induced recharge at the expense of reduced stream runoff.

It is concluded that the water budget “myth” is not necessarily a myth, from a basin groundwater sustainability (i.e. mass balance or water budget) perspective and that natural recharge is not necessarily irrelevant. Also, sustainable groundwater development does not always mean that interception of basin discharge (outflow) is dominant or important. In addition if basin natural recharge is small then so too must the natural discharge under the requirement of equilibrium prior to development. Interception of natural discharge must always ultimately be equal to or less than an equal rate of natural recharge, if the basin was initially in equilibrium.

It is useful to now examine the basin example given by Bredehoeft in the context of the principles outlined in this paper. Firstly, it is a precise example of Basin Maximum Sustainable Yield as discussed above in the section, Basin sustainable yield, and summarized in Table 3 with $P_d=I_d$ except that I_d only includes the natural recharge inflow (i.e. no induced recharge, hence $I_d=I_n$) and of course zero residual outflow, i.e. no evapotranspiration with $O_{rs} = 0$. As noted previously a determination of natural recharge I_n would have allowed an investigator to determine the maximum groundwater sustainable yield of this basin. In terms of the graph given in Fig. 2b the inflow in such a case would have remained constant whilst the outflow (Fig. 2c) would have decreased to zero over time until equilibrium was again achieved. Secondly, a storage depletion graph would exhibit the maximum sustenance storage depletion curve for the abstraction adopted¹². Clearly, pumping rates less than that adopted would have generated a number of different depletion curves dependent on abstraction rate, all of which would have been sustainable. However, pumping rates in excess of the rate adopted would have led to partial mining yields P_{pm} , none of which would have been sustainable.

For the alternative case considered above where the basin has a river system with a high conductivity bed meandering across the aquifer and a well field remote from the natural discharge area, the graphs would be similar to those in Fig. 2 except that there would be a smaller effect on the natural outflow. There would also be a corresponding number of storage depletion curves for pumping rates less than the pumping rate adopted, and

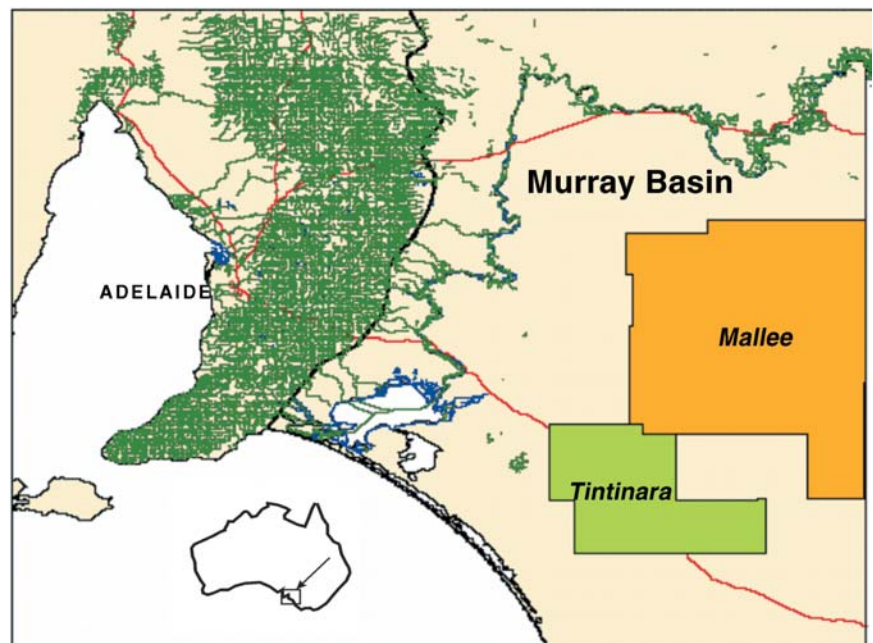
⁹ It is true to say, however, that a well field would be less desirable at this location, since simulation indicates that it would create considerably more drawdown than for the Case I and Case II before reaching equilibrium.

¹⁰ If recharge is eliminated from the numerical model (Bredehoeft 2004) then so too must discharge under pre-development conditions. In this case, the numerical model would always default to a mining yield case (no equilibrium could be achieved) unless there is sufficient surface water available in the form of stream depletion say to sustain the basin abstraction.

¹¹ This runoff would be generated from the hills of hard rock surrounding the alluvial aquifer and could also include baseflow from this area. Groundwater in the hard rock could be considered for the most part to be part of the unrecoverable storage as given in this paper.

¹² In this case, the sustenance storage used to achieve equilibrium can be calculated to be up to 3% of the total storage for this example.

Fig. 7 Mallee region groundwater system-Murray Basin, South Australia (after Barnett 2002)



also a series of curves for rates higher than the pumping adopted in the original example. All of these would have led to sustainability because of runoff water being available through stream depletion.

Finally, an ecological constraint in the Bredehoeft example (e.g. limitation of drawdown effect on plant growth) would have required maintenance of residual outflow (evapotranspiration). Groundwater development and use in this basin would therefore have been severely limited irrespective of the location of the well field although such growth could have been maintained for a longer period with the well field situated at the recharge end of the basin.

Basin sustainability yield constraints

As noted previously, the basin or groundwater entity sustainable yield might be subject to production facility constraints. For example, assume two such constraints such as pumping economics and subsidence both of which could be expressed in terms of a maximum or critical drawdown for each production facility. In the numerical model of the basin these drawdowns (or maximum flow rates) could be applied to a well field(s) or even individual wells beyond which pumping becomes uneconomic or create undesirable drawdown in the case of potential subsidence¹³. The model could then be run not to an arbitrary time frame or period but for a much longer time to test for equilibrium. In the process some production facilities may fail while others reach steady state.

¹³ For example, in the commercially available Modflow-Surfact code (Hydrogeologic 1996a) maximum drawdown can be set in the production facility or facilities so that these levels are not exceeded during the simulation by automatically reducing respective pumping rates during the simulation.

The result would define the permitted sustainable yield of the basin for this configuration and indicates the life expectancy of the production facilities that ultimately fail and the time over which this will occur. Alternatively it may indicate that the system as a whole is not sustainable but is a partial mining basin yield.

Whether the time to equilibrium be 20 years or 2,000 years under a sustainable scenario, it is important to state the time duration in the model assessment and then if necessary indicate the likely drawdown magnitudes over a selected planning period horizon based on the model results.

Mallee regional groundwater system - Murray Basin, South Australia

Barnett (2002) presents a numerical model example of a large geologically unbounded groundwater area, that is, a groundwater entity as discussed above. The locality is as shown in Fig. 7, and water balances are illustrated in Fig. 8.¹⁵ The aquifer system is composed of a 100-m to 140-m-thick limestone and is used for irrigation, town water supply and stock and domestic purposes. The potentiometric surface is some 40 m below natural surface. The climate is semi-arid and rainfall recharge is less than 1 mm/year. There are no major surface water streams across the designated area. The groundwater, containing 3,000 mg/l total dissolved solids, is thought to be largely a fossil remnant of an ancient wetter climate. Storage volume is estimated at 10^8 ML. Based on numerical model analysis total pre-development inflow of 6,727 ML/year is comprised of: 745 ML/year rainfall recharge; 3,850 ML/year upward leakages from an underlying aquifer and 2,132 ML/year of lateral aquifer inflow. Pre-development outflow of 6,722 ML/year is comprised of: 6,522 ML/year lateral aquifer outflow and 200 ML/year

upward leakage to a smaller limited-size overlying unconfined aquifer.

There are no ecological constraints for this groundwater zone because of the depth of the water table and potentiometric surface. Model simulation has indicated that 30 years of production at a rate of 60,000 ML/year will increase the total inflow rate to 11,040 ML/year comprising: 745 ML/year rainfall recharge; an increase to a total 7,760 ML/year upward leakage; downward leakage of 100 ML/year and increase of lateral inflow to 2,435 ML/year. The total residual outflow of 2,930 ML/year will be less than the pre-development rate, entirely due to interception of part of the pre-development lateral outflow.

In this case, the natural pre-development rate of inflow is 6,727 ML/year whilst the total induced rate of recharge would be 11,040 ML/year, which is only just over 18% of the proposed abstraction rate. It is quite evident, given there are no surface sources available over the designated area for significant inducement of inflow, and that the abstraction is not sustainable. It is clear that this is a partial mining yield situation within and most probably beyond the 30-year planning period. The storage volume however is obviously very large and would service such a yield well beyond the planning period.

Barnett (2002) points out that the proposed use is calculated to be about 2% of the total storage. He also states that this depletion will accrue tangible benefits. Such benefits would include first, sustaining future generations through irrigation usage who otherwise would probably not prosper without such pumping and secondly ultimate reduced saline water discharges to the Murray River, which is located some distance well beyond the groundwater area.

The corollary here is that defining a sustainable yield based on capture of natural and induced recharge and intercepted outflow would not be possible for this groundwater entity. An interesting question, however, would be: what management plan would have been followed if this system had been constrained by ecological issues?

Southern High Plains Aquifer, USA

The second example is the well-known Southern High Plains Region of Texas (SHPR) in the United States, chosen because this area is not unlike many of the arid to semi-arid groundwater systems encountered in other parts of the world that largely contain a fossil remnant groundwater system from a past wetter climate. It is therefore a useful analogue to study and to benefit from in formulating abstraction policies for similar systems in other dry parts of the world.

Kazmann (1988) gives a good summary of the SHPR groundwater system. Groundwater occurs in the Ogallala formation comprising poorly cemented fine sand and silt with some coarse sand and gravel ranging in thickness from 85 to 120 m. The aquifer is bounded by the High Plains escarpments.

Prior to development, the aquifer had an average depth to water from the surface of about 26 m. Groundwater abstraction for irrigation commenced in about 1911 and was small with 300 wells in operation before 1935. In 1935 the area irrigated was 1.6×10^4 ha that increased to 1.6×10^6 ha in 1960. Total aquifer storage prior to development was estimated at 2.5×10^8 ML. About 25% of this storage was withdrawn by 1962 and up to 40% by 1984.

Rainfall recharge to the system has been estimated in the range 6.3×10^4 to 1.3×10^5 ML per year. Yearly pumping was on average 2.5×10^6 ML. Hence, recharge to the aquifer system based on these figures was in the range 2.5 to 5% of the volume pumped. This is clearly a partial mining, and close to a mining yield situation.

A sustainable yield policy would have limited the abstraction to a maximum rate somewhere in the range 2.5 to 5% of the final pumping rate and less if all residual outflow had not been intercepted. Such a policy would not have allowed the area to be economically viable for more than about 70 years.

Kazmann (1988) notes that “(this) groundwater deposit must be considered exhaustible, like oil or gas, and the final outcome of the mining operation can be anticipated and proper provisions must be made by each individual who is affected.” One lesson that has been learned in this case is that groundwater needs to be used efficiently and not wasted.

Discussion and considerations

The ideas and concepts discussed in this review, and based on the authors' experience, have led to enunciation of the following points that require consideration when developing strategies for sustainable use of groundwater:

- Confusion about the concept of sustainable yield has arisen because of a perceived need for a terminology that can be applied universally. It is more important, however, to understand how a particular aquifer system works so that impacts resulting from its use can be predicted and allowed for in resource planning. Use of the term where it is not warranted is misleading.
- It would be better to view groundwater not as a renewable resource but as a mineral resource that can be replenished under certain circumstances and geographical locations. This perspective is particularly relevant in drier parts of the world such as Spain, parts of South America, North America and China, inland Australia, the Middle East, Northern Africa, parts of Russia, and the Mediterranean area.
- The use of the term “over-exploitation” in the context of this paper means storage depletion in excess of the maximum sustenance storage of the basin or groundwater entity and/or where water quality has deteriorated as a result of abstraction. Use of the term gives the lay impression that this means unbridled use and that measures could always be introduced or applied to prevent this from happening. Whilst prevention may

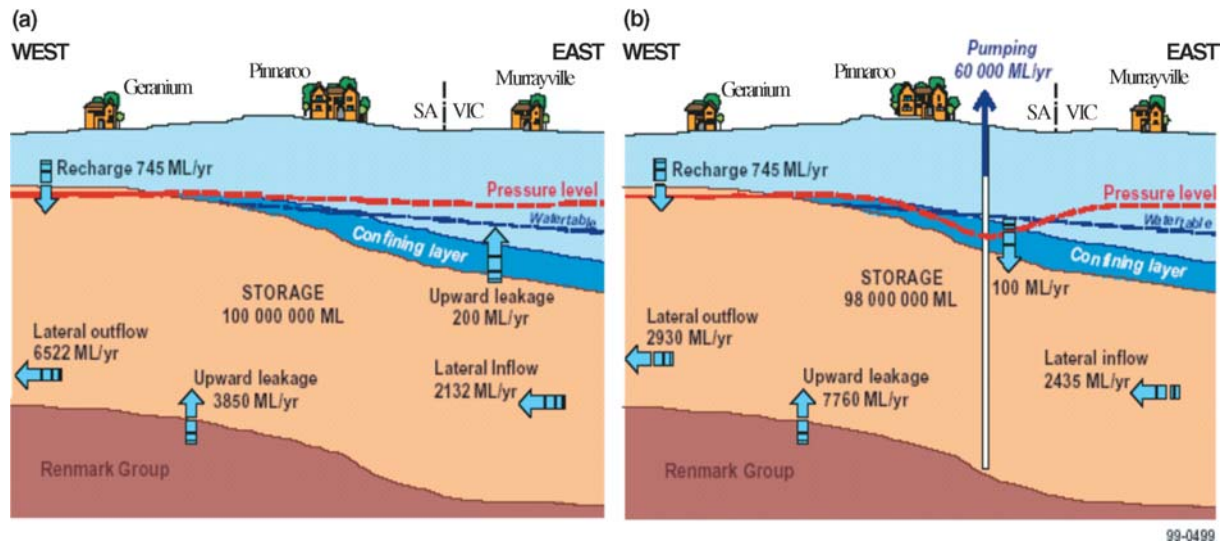


Fig. 8 Conceptual cross-sectional diagram, not to scale, showing water budget for the Mallee region (a) before irrigation (b) after 30 years of ‘permissible annual volume’ (PAV) irrigation (after Barnett 2002). Section is oriented east-west; marked “Mallee” in Fig. 7

be possible where groundwater replenishment is adequate or abstraction reduction is possible, it has to be recognised there will be situations where groundwater cannot be economically or sensibly developed under a sustainable yield policy. That is, sustainable development of groundwater resources may simply not be feasible in many drier parts of the world. In this respect, there is agreement with some of the relevant views on sustainability given by Price (2002). The words ‘non-sustainable use or usage’ could be used as an alternative.

- The ideas given in this paper have been presented to community representatives (Kalf and Woolley 2004) interpreted in the form of an analogous bank balance with deposits and withdrawals. It is interesting that their response has been that they would prefer to know how long abstraction will last, rather than be under the impression that the groundwater is “sustainable,” or can be made to be sustainable under a regime of severe, unreasonable and uneconomic restrictions to prevent “overdraft” that is, mining of an aquifer system.
- For numerical model based sustainable yield assessments, use of the flux based streamflow package (i.e. Prudic 1989; HydroGeologic 1996b) rather than the head based river flow package is suggested for users of the USGS MODFLOW program or more advanced commercial variants of the computer code. The flux based package allows a more realistic mass balance of both surface and groundwater systems in sustainable yield determination. Output¹⁴ such as shown in Fig. 2 split into its inflow and outflow components is encouraged in reporting sustainable yield simulations

¹⁴ Such output is currently not readily available in convenient files for plotting in most MODFLOW packages—developers should address this deficiency.

including a graphical cumulative mass balance of the same components. Such simulations would preferably explore sustainability by testing for equilibrium in the time domain in addition to well field drawdown response (subject to constraints) over time, and not just to an arbitrarily chosen time frame. Such output can form the basis of deciding the permitted sustainable yield and sustainable development by selecting a given curve or curves based on the applied constraints and particular abstraction scenarios.

- Analytical models are considered unsuitable for basin or groundwater entity sustainable yield estimation mainly because they lack the ability to simulate output mass balance but also because their treatment of inflow and outflow component interaction cannot be rigorous and their response is based on linear superposition theory. These models would be better limited to local well interference and stream depletion calculations and ‘first-pass’ assessments. Sustainable yield calculation based on water level response alone using such models is not considered suitable.
- The use of storage depletion greater than sustenance storage, coupled with an arbitrary time frame as a guise for claiming sustainability, is not recommended irrespective of the volume in storage. This approach might be acceptable for water supplies for mining projects where abstraction is of relatively short and finite duration (Anderson et al. 2002), provided of course that the consequent long to very long period of recovery can be tolerated. But for on-going water resource projects particularly where abstraction generally increases over time it could give stakeholders a false sense of security and be quite misleading in the long term. It would be better to advise stakeholders of the time for exhaustion of the resource, where applicable, so that adequate contingency measures can be put into place if necessary.

- In a perfect world, questions about whether sufficient water to sustain civilised communities indefinitely can be withdrawn from natural systems and what size those communities should reach, would perhaps be asked and answered before the communities began to withdraw the water. Human civilisation is not like that however, and it is nearly always the case that the rate of use of a resource outstrips knowledge of what the implications of that use might be. In the case of water, human civilisation now finds itself in two broad camps. On the one hand, wealthy civilisations are now approaching a level of knowledge that might provide answers to such questions, but resource use levels in some areas may be such that those answers may not always be palatable. On the other hand, in poorer or less developed parts of the world the current level of resource use may be insignificant, and completely sustainable, but those communities do not have the wealth or knowledge with which to address the questions of sustainability as they endeavour to emulate the more developed parts of the world. One might think, perhaps, that the concepts discussed in this paper are therefore irrelevant and that in the long run wealth will succumb to the power of nature and only subsistence communities will survive. On the contrary, if communities properly understand these issues, sufficient advance notice may be provided to enable long-term strategies to be devised in highly developed areas. Concurrently, knowledge transfer between developed and less developed communities may lead to better resource management outcomes rather than disasters.
2. Production facility yield and sustainable (basin or groundwater entity) yield need to be differentiated in sustainability assessments
 3. Sustainable yield implies that the basin or groundwater entity water balance reaches equilibrium at some time
 4. The term “sustainable” should not be used where it is not necessary or warranted
 5. An arbitrary time frame should not be used to define the sustainable yield
 6. Aspects such as, for example, economic pumping, subsidence, water quality of the production facilities and ecological requirements can be applied as constraints in determining sustainable basin or groundwater entity yield
 7. Use of storage depletion greater than sustenance storage, as defined herein, coupled with an arbitrary time frame for claiming sustainability is not recommended
 8. Numerical models are the preferred method to determine the basin sustainable yield. Analytical models are unsuitable for such a determination
 9. Water level response over time can be ambiguous in determining sustainability of the groundwater system
 10. Use of the term “non-sustainable use or usage” would be preferable to the term “over-exploitation”
 11. Estimation of basin or groundwater entity pre-development recharge is a relevant activity in the determination of the sustainable yield although it may or may not be important, often depending on the availability of surface water runoff sources to groundwater systems
 12. Stream-aquifer interaction using flux based algorithms is the preferred method for sustainable yield determination using numerical models
 13. Variation in climate and land-use changes will produce uncertainty in any determination of basin sustainable yield and hence probability methods of numerical model solution are suggested
 14. Irrespective of the time to equilibrium, under a sustainable yield scenario it is important to state the time duration to such a condition in the model assessment as well as determining drawdown response over a selected planning horizon as required.

In this paper, the authors have sought to provide an unambiguous methodology of determining sustainable yield, including the non-sustainable partial mining and mining yield concepts. This can only be achieved by basing it on sound physical principles, thereby removing the possibility of varying interpretations and misinterpretations deriving from other issues. Aspects of groundwater management factors affecting production facility discharge should be regarded as constraints on the way the physical system is used, and not as part of the basic physical concept. The law of conservation of mass (i.e. the continuity equation) is unequivocal, and leaves no room for misinterpretation. This law must be the basis of the assessment of sustainable yield with those constraints applied as necessary in determining optimum usage patterns for particular circumstances.

Conclusions

The main advice and key points made in this paper can be summarized as follows:

1. Sustainable yield is best determined in the context of the basin or groundwater entity water balance

Appendix

Summary of selected worldwide water budget approaches

Use of some type of water budget approach is now common in many countries. The following Table 2 is based on contents in Evans et al. (2003) plus some additional references (as indicated) and personal knowledge. This table is by no means exhaustive but illustrates that the approaches even in developed countries are often very basic and use outmoded and/or ambiguous concepts.

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