Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 89 (2014) 347 – 354
Procedia Engineering
www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

A New Approach to Urban Water Management: Safe and Sure

D. Butler *, R. Farmani, G. Fu, S. Ward, K. Diao, M. Astaraie-Imani

Centre for Water Systems, University of Exeter, Exeter, EX4 4QF, UK

Abstract

This paper introduces a new approach to water management that is 'Safe & SuRe'. This includes presenting a conceptual framework to link the emerging threats of climate change and variability, rapid urbanization and population growth, energy constraint and tightening environmental regulation through to their consequences on social, economic and environmental recipients. The framework allows identification of the role and need for mitigation, adaptation and coping strategies. The paper proposes definitions and discusses what engineering, organizational and/or social options can potentially develop the degree of resilience and sustainability needed to deal with these 21st century threats. The paper goes on to propose how these approaches might be objectively assessed and identifies gaps in our knowledge that require further research.

Peer-review under responsibility of the Organizing Committee of WDSA 2014

Keywords: Adaptation; coping; mitigation; reliability; resilience; safety; sustainability; water management.

1. Introduction

The global water sector faces immense challenges in the 21st century and two of the most significant relate to climate and population. Climate is changing and year 2080 projections for the UK, for example, indicate that there will be significant rises of average summer temperatures (3-4°C), winters will become wetter, summers drier and there will be more frequent, extreme weather events [1]. As if to confirm this, England and Wales suffered one of the ten most significant droughts of one to two years duration in the last 100 years up to March 2012 [2]. Indeed, several water companies in the south-east of England introduced hose-pipe bans in early April 2012 with further restrictions planned if conditions persisted. From April 2012 however there was a significant change in weather patterns across the country with the year ending as the second wettest on record [3]! The implications for water resources and water demand have been well-rehearsed [4].

* Corresponding author. Tel.: +44-1392-724064
E-mail address: d.butler@exeter.ac.uk

Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.198

Nomenclature

Rel	reliability
Res	resilience
Sus	sustainability

In England and Wales, the current population of 63 million will swell by a further 9 million by as soon as the 2030s. At the same time, up 5% from today, 18% of the population is projected to live alone leading to commensurate reductions in household occupancy [5]. Both factors will have significant effects on water demand and both threats are a significant challenge to the water sector. Taken in isolation existing approaches may be able to cope, but considered together with other threats (e.g. greenhouse gas reductions, tightening environmental legislation), and the speed, magnitude and uncertainty of future change, *at best* levels of service will be threatened and more costly and unpopular engineering interventions will be needed.

A new approach is needed to tackle these 21st century threats and a new vision is needed for water management in cities, which is Safe & SuRe: that is systems designed not just for safe provision of services but also to be more sustainable and resilient to emerging threats. Sustainability and resilience are both dynamic concepts (although over different timescales) that can be increased; not only to avoid negative impacts but also to promote positive ones, yet neither being at the expense of reduced safety.

Sustainability is not a new concept and by the 1990s sustainable water systems were being defined as those ‘designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity’ [6]. However, this has been difficult to achieve in practice because, when considered as an outcome, is difficult to crystallise. When considered as a process, however, more sustainable water management becomes a realistic target [7]. Resilience on the other hand is a newer concept yet still has a rich literature from many disciplines. There are two fundamentally different viewpoints of resilience – engineering and ecological [8]. Engineering resilience essentially focuses on ensuring efficiency of function following failure (system performance) whereas ecological resilience majors on maintaining existence of function (system integrity). It is the former meaning that is pursued further here and will be defined in detail later in the paper.

This paper introduces the new concept of Safe & SuRe Water management including presenting a conceptual framework to link the emerging threats of climate change and variability, rapid urbanisation and population growth, energy constraint and tightening environmental regulation through to their consequences on social, economic and environmental recipients. This includes the role of mitigation, adaptation and coping strategies. The paper proposes definitions of key concepts and discusses what engineering, organisational and/or social options or approaches can potentially develop the degree of resilience and sustainability needed to deal with these 21st century threats and proposes how these approaches might be objectively assessed.

2. The Safe and SuRe framework

A conceptual framework has been developed, designed to show how the emerging threats mentioned above link through to their ultimate consequences on society, the economy and the environment (Fig. 1). It also clarifies the role of the city water infrastructure in mediating between threat and impact through compliance with defined levels of service. This is similar to a pressure-state-response or ‘DPSIR’ type framework, but emphasises the need and place for interventions. Key to developing a ‘Safe & SuRe’ system is to understand what interventions are required, for what reasons and by whom, particularly in three distinct ways: mitigation, adaptation and coping.

In this work, mitigation refers to reducing the threat. This typically denotes long-term actions, which although carried out locally will have a much wider benefit (e.g. city, nation, world). Adaptation is the routine business of the water sector and is a local response to increasing threats, typically expressed as efforts to increase system reliability and resilience. Coping, on the other hand, refers to how water service customers can be better protected or prepared for impact should mitigation and adaptation be insufficient (e.g. decreasing the recipient vulnerability and developing social capacities). To be Safe & SuRe, all these interventions must also ensure system sustainability.

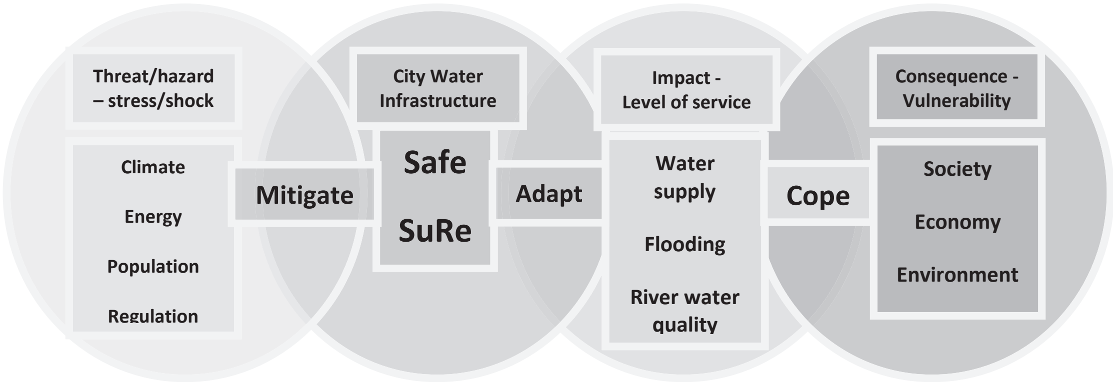


Fig. 1. Safe & SuRe intervention framework.

3. Definitions

3.1. Safe

In this work we use the word 'safe' as a synonym for 'reliable' where reliability is concerned with the probability of successful operation of the system [9] or more precisely the probability of the system being in a non-failed state [10]. We define it as: "*the degree to which the system minimises level of service failure frequency over its design life when subject to standard loading*".
The goal of a reliable system (*Rel*) is to avoid or prevent failure:

Rel = min (**failure**: *probability*) (1)

3.2. Resilient

Resilience is a more challenging word to define as it has a number of different, though seeming similar, definitions. Some definitions tend to treat it as a desirable state or characteristic where continuity of normal system operation is the goal [13]. For example, the water sector financial regulator in England and Wales (OFWAT) regards it as the ability of the system to withstand shock and continue to function [11]. On the other hand, the US National Infrastructure Advisory Council (NIAC) defines a resilient system as one that reduces the magnitude and/or duration of disruptive events, stressing the 'bouncebackability' [12]. This is mirrored somewhat by the US RESIN project which defines a resilient system as one that gracefully degrades and subsequently recovers from a failure event [14]. In all cases, the emphasis is on how the system responds **after failure** to **unexpected loading conditions**. In this work, we define resilience as: "*the degree to which the system minimises level of service failure magnitude and duration over its design life when subject to exceptional conditions*".
The goal of a resilient system (*Res*) is therefore to both withstand service failure as much as possible and to recover from it if and when it occurs:

Res = min (**failure**: *magnitude, duration*) (2)

3.3. Sustainable

Sustainability is usually expressed as a set of socially derived goals or capitals combining social equity, economic viability and ecological integrity [15, 16] sometimes shortened to 'people, profit, planet'. The key notion is that these capitals should be maintained or even enhanced for future generations (well beyond any engineering design horizon). Given the difficulty in recognising these goals and their trade-offs in specific contexts, sustainability is arguably better thought of as a journey or trajectory rather than a fixed state [17] and is defined here as: *"the degree to which the system maintains levels of service in the long-term whilst maximising social, economic and environmental goals"*.

The goal of a sustainable system (*Sus*) is therefore to continue functioning over the long-term balancing agreed societal goals:

$$Sus = \max\ (\textbf{capital}: \text{social, economic, environmental}) \tag{3}$$

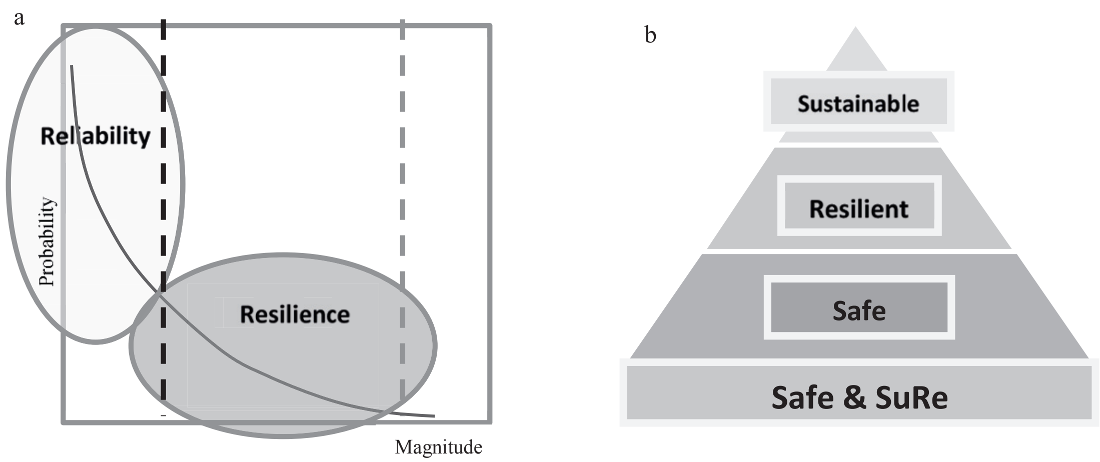


Fig. 2. (a) Relationship between reliability and resilience; (b) the Safe and SuRe pyramid.

3.4. Relationship between reliability, resilience and sustainability

Reliability is the bedrock of the Safe & SuRe concept. It ensures that the system performs its function well and is the core business of the water sector. Reliability is usually measured in relation to expected or regulated levels of service. Resilience is the property and/or performance of the system when the level of service has not been attained for whatever reason, but particularly when subject to unexpected or exceptional disturbances. Fig. 2 (a) shows how reliability and resilience are related with respect to the probability and magnitude of a disturbance. Intuitively, the two aspects are related with resilience building on reliability. However, the detailed relationship between the two is currently unknown. Sustainability is predicated on a long term horizon so by necessity requires the design of resilient systems that can cope with any disturbances that may appear in the future [18], and resilience is therefore a key underpinning concept in operationalising sustainability [19]. Again the detail of the relationship between the two is unknown so it is not currently possible to clearly understand how to maximise sustainability by building resilience.

In terms of set theory, safety/reliability is necessary but not sufficient for resilience, and resilience is necessary but not sufficient for sustainability [20]. To be Safe & SuRe, a system must be reliable, built upon by resilience and topped off with sustainability (Fig. 2 (b)). The characteristics of such a system are summarised in Table 1.

Clearly, there is some tension here between reliability and resilience referring to different domains (disturbance magnitude/probability) yet resilience also building on reliability. This is partly due to the disparity in definitions of resilience and partly due to a genuine uncertainty in how the two quantities relate. We hope to resolve this as the work unfolds.

Table 1. Characteristics of Safe & SuRe systems.

Safe	Timescale	Performance objective	Level of service (LoS)	Attributes
Reliable	Design life	Avoid failure	Within LoS	Resistant
			Normal	Stable
			High probability	
SuRe				
Resilient	Design life	Overcome failure	Outside LoS	Redundant
			Extreme	Connected
			Low probability	Flexible
Sustainable	Extra-design life	Endure failure	Challengse LoS	Equitable
		Balance demands	Exceptional	Affordable
			All probabilities	Low impact

4. Building resilience

4.1. Dimensions

When (engineering) resilience is being discussed there are essentially three different dimensions or types being referred to: attribute-based, performance-based and technology-based.

Attribute-based resilience, also referred to as **general resilience**, refers to the state of the system that enables it to limit failure duration and magnitude to any threat (all hazards). It concerns the system as a whole, is typically (though not exclusively) descriptive in nature and could be considered as a set of design principles e.g. the degree of interconnectedness or duplication. This might be better termed **design resilience**. Specific attributes are discussed below.

Performance-based or **specified resilience** refers to the agreed performance of the system (or part of the system) in limiting failure duration and magnitude based on a particular threat. It is therefore typically prescriptive (*i.e.* standard-based), often quantitative and refers to an operational goal. This could be called **operational resilience**. Example standards are discussed below.

Technology-based resilience refers to equipment that can improve the preparedness of the user for extreme events. This is perhaps most well developed in terms of flood resilience where a range of devices are available to limit flood damage and speed recovery [21]. However, rainwater harvesting systems and garden water butts/barrels perform a similar function during water shortage.

4.2. Attributes

Wildavsky has proposed a set of attributes or principles of resilient systems based on the development of capacities to cope with uncertainty and surprises whilst maintaining overall system performance (sustainability?) [22, 23, 24]:

1. **Homeostasis**: systems are maintained by feedbacks between component parts that signal changes and can enable learning. Resilience is enhanced when feedbacks are transmitted effectively.
2. **Omnivory**: external shocks are mitigated by diversifying resource requirements and their means of delivery. Failures to source or distribute a resource can then be compensated for by alternatives.
3. **High flux**: the faster the movement of resources through a system, the more resources will be available at any given time to help cope with perturbation.

4. **Flatness**: Overly hierarchical systems with rigid chains of command are less flexible and hence less able to cope with surprise and adjust behaviour. Top-heavy systems will be less resilient.
5. **Buffering**: a system that has a capacity in excess of its needs can draw on this capacity in times of need, and so is more resilient.
6. **Redundancy**: A degree of overlapping function in a system permits the system to change vital functions to continue while formerly redundant elements take on new functions.

Homeostasis in water distribution networks may be enhanced by improved sensoring to provide real-time information of system operation. Key to this is that systems are put in place to receive, interpret and respond to alarms and other indicators of drops in system performance or failure. Omnivorous water systems have several or indeed many sources of supply. This allows switching of one supply to another should operating conditions dictate. High flux systems are those with high capacity, perhaps greater than is strictly required to supply the design load. Flat systems could be characterised as those with ubiquitous sensors/controllers throughout the system ensuring equitable levels of service [25]. Buffering in the system will typically be the headroom in the water resource system that relates to the difference between supply and demand. Finally, redundancy can refer to duplicated equipment (*e.g.* pumps or pipes). The difficulty with all these attributes is knowing *a priori* how to characterize them and then how much is required of each.

4.3. Standards

Standards for resilience are not common in the water sector, or at least not explicit ones. There is a significant debate about this in the British water sector and Ofwat [11] has set out several proposals for such resilience-based standards. Two examples relevant to this work are:

- **System standards** (attributes): related to the spare capacity and redundancy to be provided *e.g.* 12 hours emergency storage in service reservoirs, dual power supplies, every customer to be supplied by at least two separate sources.
- **Service standards** (performance): related to the service quality provided *e.g*. minimum pressure standards, 10 l/hd/day to be provided within 24 hours of a loss of supply.

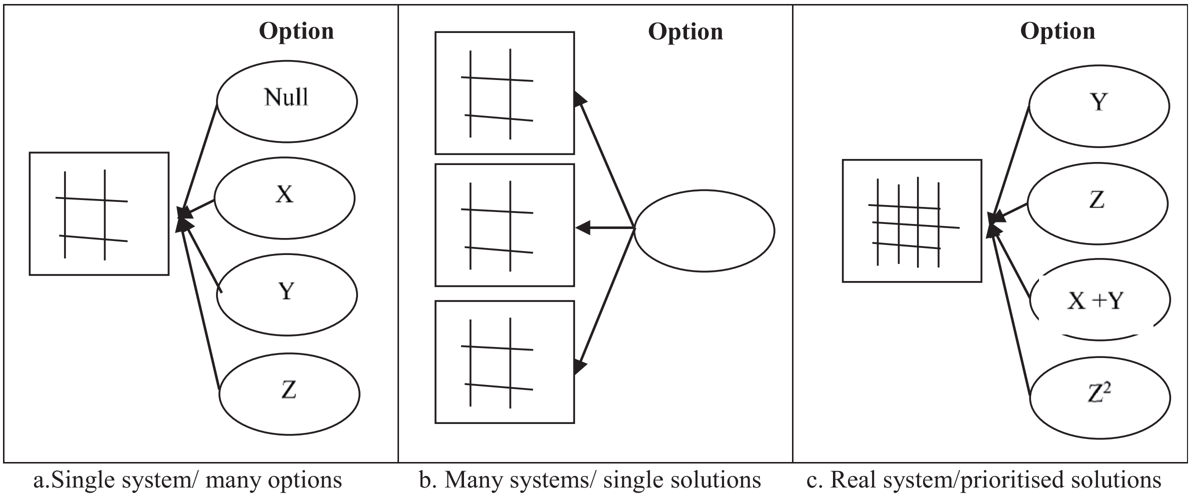
Measures of success or compliance might then be [11]:

- Compliance with system standards: *e.g.* all populations above a certain size should not be vulnerable to single points of failure.
- Compliance with service standards: *e.g.* limit disruption to say 1 day per 10,000 population per year.

As the project progresses we intend to further develop, extend and test these and other standards.

4.4. Strategies

In the Safe & SuRe project and referring to Fig. 1 we have defined three key intervention categories: mitigation, adaptation and coping. It might be argued that relatively few of these three intervention types can be delivered by the water sector. Whilst it is true that many approaches will need to be undertaken in partnership, the water sector has roles and responsibilities in all three types. It should also be recognised that the type of intervention may be threat-specific and one intervention will not fit all threats. The question arises, what specific strategies or options (e.g. design, operation, technology, policy) can enhance resilience and deliver Safe & SuRe systems?



Fig, 3. Proposed option/strategy assessment framework.

Examples strategies include:

- Scale (e.g. centralised, decentralised, hybrid).
- Low tech (e.g. water butts, zeroscaping).
- High tech (e.g. smart sensors, real time control).
- Flexibility (e.g. option portfolios, incremental build)
- Emergency planning (e.g. emergency boils, bottled water).
- Policy change (e.g. planning controls, building regulations).
- Behavioural change (e.g. coping strategies, education).

Work is on-going to list, characterise, categorise and cost these options and strategies.

5. Strategy assessment framework

The key challenge is to link these attributes, options and strategies to performance. This can potentially be accomplished either by direct evaluation or, more usefully perhaps, by first devising indicators of general resilience and then linking them in turn to specified resilience. Current evaluation approaches typically look to evaluate options either on a case by case basis or solution by solution. The proposed approach consists of a three phase systematic evaluation of multiple options:

1. A single system benchmark analysis with many options (Fig. 3a),
2. Analysis of many (synthetic) systems with single solutions (Fig. 3b)
3. Confirmation on real case studies with prioritised solutions (Fig. 3c).

The outcome of this approach should lead to a strongly quantified and generalised outcome.

6. Conclusions

This paper has outlined a new approach to water management in cities which argues that 21st century systems need to be reliable, resilient and sustainable: Safe and SuRe. Such systems are required because of the significant challenges that lie ahead this century, not least the high uncertainty and variability to be faced. Existing 'fail safe' approaches are essentially unaffordable and indeed unachievable. Nurturing 'safe to fail' thinking is needed to manage contemporary change and uncertainty. A key aspect of the paper has been exploring the definition of terms and in particular exploring the concept of resilience as a way of managing system failure. Further, the paper has explored the relationship between reliability, resilience and sustainability. Whilst it is intuitively clear that they build upon each other a major unresolved issue is how exactly that is achieved. To do this, further work is needed to develop quantifiable indicators of design (general) resilience and then to relate that to operational (specific) resilience. Further work is needed to explore how the whole range of available mitigation, adaptation and coping strategies can build resilience and sustainability. Already, it is clear that there is no 'magic bullet' and no 'one size fits all' but that a range of approaches, scales and actors is key to ensuring our water management systems are Safe & SuRe.

Acknowledgements

This work forms part of a research fellowship for the first author funded by the UK Engineering & Physical Sciences Research Council (EP/K006924/1) and supported by the Environment Agency, the Consumer Council for Water, the Welsh Government, the Environmental Sustainability KTN, the Water Industry Forum, Severn Trent Water, Northumbrian Water, Arup, Black & Veatch and ACO Technologies.

References

[1] http://ukclimateprojections.metoffice.gov.uk/ (02/04/2014)
[2] http://www.metoffice.gov.uk/climate/uk/interesting/2012-drought (02/04/2014)
[3] http://www.metoffice.gov.uk/news/releases/archive/2013/2012-weather-statistics (02/04/2014)
[4] J.W. Hall, G. Watts, M. Keil, L. de Vial, R. Street, K. Conlan, P.E. O'Connell, K.J. Beven, C.G. Kilsby, Towards risk-based water resources planning in England and Wales under a changing climate, Water and Environment Journal, 26 (2012) 118–129.
[5] ONS, 2008-based National Projections Statistical Bulletin, Office of National Statistics, 2009.
[6] D.P. Loucks, J.S. Gladwell, Sustainability Criteria for Water Resource Systems, UNECO International Hydrology Series, Cambridge University Press, 1998.
[7] M.B. Beck, Cities as Forces for Good in the Environment: Sustainability in the Water Sector, University of Georgia, Athens, 2011.
[8] C.S. Holling, Engineering Resilience versus Ecological Resilience, in: P. Schulze (Ed.), Engineering Within Ecological Constraints, National Academy of Engineering, 1996.
[9] D. Jung, D. Kang, J.H. Kim, K. Lansey, Robustness-based design of water distribution systems, J. Water Resources Planning & Management (2013) doi:10.1061/(ASCE)WE.1943-5452.0000421.
[10] T. Hashimoto, D.P. Loucks, J. Stedinger, Reliability, resilience and vulnerability for water resources system performance evaluation. Water Resources Research, 18 (1982) 14-20.
[11] Ofwat, Resilience – outcomes focused regulation. Principles for resilience planning, The Water Services Regulation Authority for England & Wales, 2012.
[12] NIAC, Critical infrastructure resilience - Final report and recommendations, 2009.
[13] R. Francis, B. Bekera, A metric and frameworks for resilience analysis of engineered and infrastructure systems. Reliab. Eng. Syst. Safety, 121 (2014) 90–103.
[14 K. Lansey, Sustainable, robust, resilient water distribution systems, 14th Water Distribution Systems Analysis Conference. Engineers Australia, 2012, 1–18.
[15] D. Satterthwaite, The Earthscan Reader in Sustainable Cities, Earthscan Publications, London, 1999.
[16] M. Jenks, C. Jones, Dimensions of the Sustainable City, Future City, 2, Springer, New York, 2010.
[17] D. Butler, J.W. Davies, Urban Drainage, third ed, Spon Press, London, 2010.
[18] R.W. Scholz, Y.B. Blumer, F.S. Brand, Risk, vulnerability, robustness, and resilience from a decision-theoretic perspective, Journal of Risk Research 15 (2012), 313–330.
[19] S.T.A. Pickett, B. McGrath, M.L. Cadenasso, A.J. Felson, Ecological resilience and resilient cities. Building Research & Information, 42 (2014) 143-157.
[20] D. Blockley, J. Agarwal, P. Godfrey, Infrastructure resilience for high-impact low-chance risks, Proc. Institution of Civil Engineers, Civil Engineering, 165 (2012) 13-19.
[21] W. McBain, D. Wilkes, M. Retter, Flood Resilience and Resistance for Critical Infrastructure, Report C688, CIRIA, London, 2010.
[22] A. Wildavsky, Search for safety. Transaction Publishers, New Brunswick, 1988.
[23] K.E. Watt, P.P. Craig, System stability principles. Systems Research, 3 (1986) 191–201.
[24] U. Hassler, N. Kohler, Resilience in the built environment, Building Research & Information, 42 (2014) 119–129.
[25] M. Fliess, J. L. Lévine, P. Martin, P. Rouchon, Flatness and defect of non-linear systems: introductory theory and examples. International Journal of Control, 61 (1995) 1327-1361.