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DESIGN PRINCIPLES FROM TRADITIONAL MOUNTAIN IRRIGATION SYSTEMS (*BISSES*) IN THE VALAIS, SWITZERLAND

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ABSTRACT The *bisses* are a traditional mountain irrigation system constructed in response to periodic water deficit during the summer months in the Valais canton of Switzerland. The origins of the *bisse* system can be traced back to the 11th century AD, but may be as old as the Iron Age. The system expanded rapidly in the fifteenth century because of economic incentives to intensify meadow production. The design principles, governance, and organization and water management strategies changed little from this period up to the end of the 19th century, despite periods of demographic and climatic change. Since this time the *bisse* system has been modernized and rationalized in line with wider structural changes to the economy and technological advancement. This paper describes some of the fundamental changes to design principles which have occurred to the *bisse* system during the 20th century and assesses the likely impacts these may have on the long term sustainability of *bisses*. These findings are then discussed in relation to other mountain irrigation systems. The wider relevance of these findings to irrigation planners of the future is also discussed.

INTRODUCTION

The Valais canton of Switzerland is one of a number of mountainous areas in the European Alps which suffer from a rain shadow effect during the summer months. Other such areas include parts of the Swiss Grisons and Engadine cantons, the Italian Val d'Aoste (Gerbore, 1995), the Austrian Tyrol, and the French Savoy and Maurienne (Kaiser, 1995). In each of these areas the traditional response has been to construct irrigation systems, principally to support vertically controlled extensive agro-pastoral farming (Netting, 1972). The *bisses* (also known as *Suonen, Wasserleitung*) are probably the best preserved and most impressive of these technologies, operating as they do in extremely rugged topography. The *bisses* of Valais have been constructed by local communities or collectives (*consortages*) who share a limited resource relationship (Crook, 1997). Figure 1 demonstrates the known construction dates of *bisses* from two inventories. It has been suggested that the system may date as far back as the Iron Age (Dubuis, 1995). There is circumstantial archive evidence for a greater number of *bisses* existing in previous centuries (Crook, 1997).

The *bisses* remain a rare example of an indigenous irrigation technology operating in a developed world context. Thus, the *bisse* system has evolved and adapted to periods of demographic and technological change which indigenous irrigation technologies in other countries are yet to pass through. This paper, therefore, is set apart from the wealth of knowledge amassed on indigenous mountain irrigation systems and strategies operating in less developed countries (e.g. Geertz, 1972; Guillet, 1987; Vincent, 1990, 1995; Gwynne and Meneses, 1994; Haagsma, 1995).

There has been much discussion about sustainable development and the concept of sustainability (e.g. Barbier, 1987; Mitlin, 1992). It has been argued that a sustainable system should demonstrate longevity, a lack of long-term irreversible environmental degradation, and a degree of intra- and inter-generational equity (Jones and Hunt, 1994; Clayton and Radcliffe, 1996). Besides this, at the level of the household, a sustainable human resource system should provide sustainable livelihoods. Few authors have attempted to examine extant irrigation systems over extensive time periods (e.g. centuries) and thus provide tangible examples of sustainability, although there have been recent calls to do so (W.M. Adams, *pers. comm.*, 1998). The *bisses* demonstrate these qualities and therefore provide a tangible example of a sustainable system (Crook, 1997). A full discussion about sustainability involves analysis of not only physical systems but also socioeconomic, cultural, and political systems (Crook, 1997). Given the constraints of space, this paper concentrates on the technical elements of the system which have promoted sustainability. Descriptions and analysis of the other parts of the system can be found in Crook (1997) and Jones *et al.* (1998). It may prove easier to transfer ideas about sustainable systems from the *bisses* of Switzerland rather than from developing world countries because of the trend to globalize from a Western European/North American modern economic society perspective (Steiner and Nauser, 1993).

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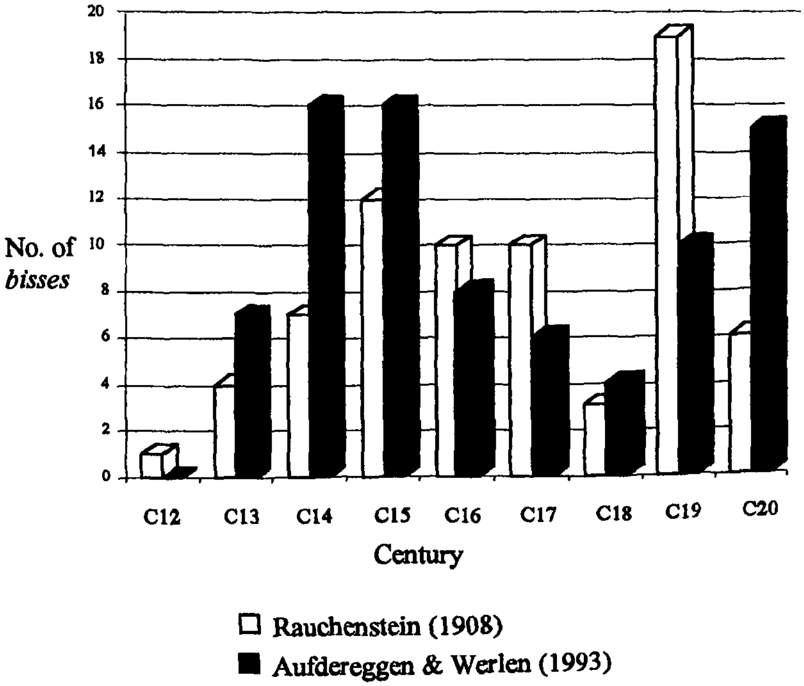

FIGURE 1. Bisse construction dates. Source: Aufdereggern and Werlen (1993) and Rauchenstein (1908).

In the 20th century, many traditional European mountain agricultural systems are seen as archaic and dependent on financial support from governments for survival (Bignal and McCracken, 1992). The *bisses* are no exception to these trends, but through a process of rationalization and modernization, the system has been adapted to meet the challenge of new intensive agricultural practices centered around the Rhône plain and valley sides and to economic development (Crook, 1997; Jones *et al.*, 1998). This paper will show that changes have not been wholesale; rather the local irrigation institutions (*consortages*) and communes have blended both traditional and modern irrigation techniques. The value of traditional *bisse* technology to other economic sectors is also being recognized and exploited by both government and non-governmental groups. This has had implications for the (re)development of *bisses*, in particular the choice of technical and material adaptations.

This paper will focus on the design principles of the *bisse* system and describe the technical changes which have occurred since the 15th century, and in particular over the last century. Where possible, reference will be made to the relationship between the design features and social, cultural, economic, and political sub-systems (Crook, 1997). These changes are discussed in relation to their implications for the sustainability of the system and how this may affect perceptions and thoughts about sustainable irrigation management. Data used in this paper are drawn from research by the first author and from work by Aufdereggen and Werlen (1993) for the *Département de l'environement et l'aménagement du territoire* (DEAT). Discrepancies in the data result from the nature of the incomplete, yet best obtainable, data set.

THE VALAIS CANTON: LAND OF THE *BISSES*

The Valais canton covers an area of 5,186 km², making it the third largest of Switzerland's cantons. The Valais is part of the Swiss territory and can be split into three economic and two linguistic regions (Figure 2). The ecumene is only a small percentage of the total surface area and had a total population of 271,291 in 1996 (OSCV, 1997). The terrain is mountainous, with Point Dufour (4,634 m) the highest peak and the shore at Lake Geneva (372 m) the lowest point. The Valais can be divided into three distinct relief zones: the Rhône valley, the lateral valleys, and the mountain areas.

The potential zone for agriculture in the Valais is very small, with only 46% of the 522,451 ha being agriculturally productive (Table 1). Productive terrain in the Haut Valais is scarcer than in the other parts of the canton, with only one third of the land suitable for farming (Loup, 1965). Each commune has a different ratio of land available at various altitudes and aspects, controlling the cultivation options of farmers (Loup, 1965: 32–35). The Valaisan productive surface includes 33% forest, 54% pasture, and 13% intensively cultivated (Cosinschi, 1994). Approximately 65% of pasture falls

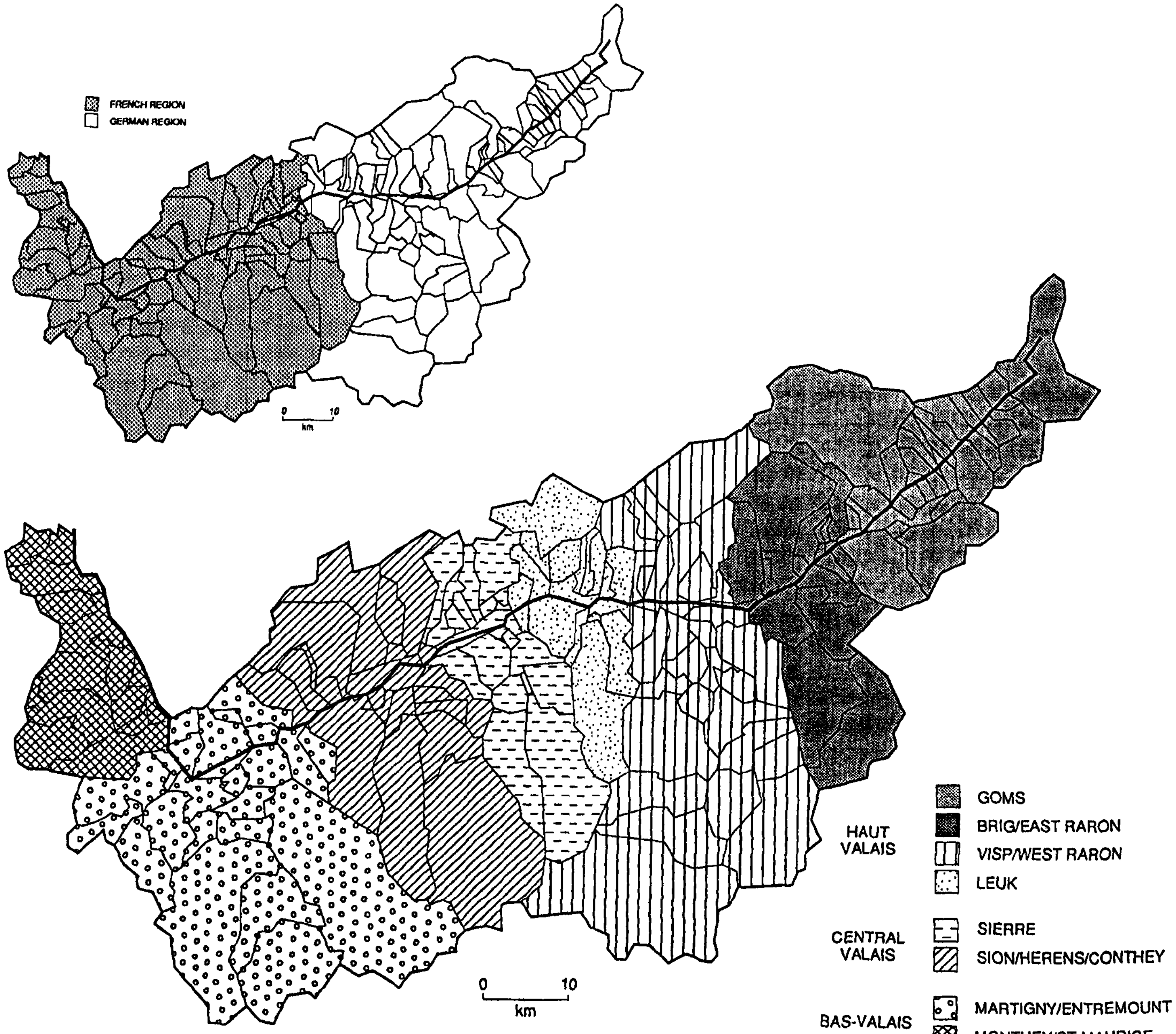

FIGURE 2. Socioeconomic and cultural boundaries in the Valais.

TABLE 1
Valais surface area and land uses (Cosinschi, 1994)

VALAIS/ WALLIS	Surface area (ha)	Woodland (ha)	Agriculture (ha)	Built environment (ha)	Unproductive land (ha)
Haut Valais	262,096	47,335	49,006	3,674	162,081
Central Valais	124,906	30,217	31,369	4,802	58,518
Bas Valais	134,393	38,397	33,084	4,481	58,431
TOTAL	522,451	115,949	113,459	12,959	280,084

within the mountain zone, with alps accounting for 7% of this total. In general, agriculture is not possible above 1,500–1,600 m, though pasture lands in favorable areas can be found as high as 2,600 m (Loup, 1965). Two thirds of the 15,000 agricultural units are found above 900 m (Cosinschi, 1994).

CLIMATE

The Valais lies within a ring of high alpine mountains and is thus partly in rain shadow, so that areas of the canton can be defined as semi-arid (UNEP, 1992: Reynard, 1995). The central Valais and the area at the base of the Mattertal and Saastal are the driest parts of Switzerland and, indeed, of the Alps as a whole (Bezinge and Bonvin, 1973). Precipitation ranges from approximately 500 mm/yr to 700 mm/yr in the Martigny-Brig area in the central Rhône Valais (Cosinschi, 1994). Most precipitation falls as snow during the winter months. The ratio of snowfall to rainfall varies according to altitude; for example, at Sion (540 m) it is 18% and Zermatt (1,610 m) 59% (Loup, 1965), such that extensive high altitude areas of the canton are glacierized.

Inter-annual variability of precipitation can be very high (Reynard, 1995); for example, Sion received 264 mm in 1921 and 956 mm in 1922 (Loup, 1965). It is common for a very dry year to be followed by a very wet year (Catzeflis *et al.*, 1972; Reynard, 1995). Even within this range, a normal year produces a water deficit that requires irrigation. Without irrigation, four in every five years farmers would fail to produce a harvest or adequate fodder (Loup, 1965). Extensive dry spells are common throughout the summer and are not unusual in both the spring and autumn as a result of föhn winds (Bouët, 1972).

In summer, temperatures are high, whereas winter temperatures can be very low. The average altitude of the 0°C isotherm shifts according to the season, reaching its lowest position in January (370 m) and its highest in August (3,630 m) (Lütschg, 1931). The thermal gradient of an adret slope is 0.5°C/100 m compared to 0.7°C/100 m on a ubac slope (Loup, 1965). Over the course of a whole slope, this can account for a 2–3°C improvement in temperature on adret slopes, making them preferential for agriculture with irrigation (Loup, 1965).

The combination of high summer temperatures, clear skies, and intense sunshine means that the central Valais and parts of the Haut-Valais have a high evapotranspiration rate (Primault and Catzeflis, 1966). Evapotranspiration is estimated at 1,200 mm, leaving a water deficit of 500 mm/yr to 700 mm/yr (Aufdereggen and Werlen, 1993). More specifically, water deficits of 300 mm often occur in the agriculturally important growing months of June, July, and August (Primault and Catzeflis, 1966; Michelet, 1995), which lead to a water deficit of around 7,000 to 9,000 m^3 ha^{-1} on meadows. The water deficit in a vineyard between the months of June, July, and August amounts to between 1,500 and 2,000 m^3 ha^{-1} (Muller, 1946). At Sion, using measurements from the period 1981-1993, evaporation rates of 120–145 mm between May and August led to smaller estimated water deficits ranging from 70-96 mm (Reynard, 1995).

TABLE 2

The spatial distribution of bisses/suon *in the Valais (after Aufdereggen and Werlen, 1993)*

Region	No. Bisses	Total Length Km
Conches	11	24
Brigue/Eastern Rarogne	30	70
Viège/Western Rarogne	76	211
Loèche	18	43
Haut Valais Total	135	348
Sierre/Val d'Anniviers	19	95
Sion, Hérens, Conthey	31	230
Martigny, Entremont	5	87
St.-Maurice	0	0
Central and Bas Valais Total	55	412
Valais Total	190	760

Irrigation can either allow crops to be grown in areas otherwise incapable of supporting them, or it can increase the number, variety, and quality of yields. The number of irrigations varies for each crop and is site specific. The principal irrigated crops are grass meadows, orchard and berry fruits, vines and some market garden crops (OSCV, 1997).

TRADITIONAL IRRIGATION

Whilst the cantonal inventory identifies 190 *bisses* (over 1 km long), not all are in operation (Aufdereggen and Werlen, 1993). There are a greater number of *bisses* in the Haut Valais than the Central and Bas Valais, but the average length of *bisses* is much longer in the latter (Table 2). These differences are determined by climatic and environmental constraints.

Emmanuel Reynard (1994 in Bratt, 1995:81) produced a further inventory from maps with a scale of 1:25,000 and all previous inventories; this gave a total number of 376 *bisses* with a total length of 1,748.5 km. Crook (1997) demonstrated that communal maps, scale 1:10,000, could provide further detail. There have been a number of estimates of the length of the distribution network, the latest produced by the DEAT stood at 25,000 km (Macherel, 1984; Aufdereggen and Werlen, 1993). The Viège/Western Rarogne region contains the highest concentration of *bisses* with 50 on the right hand bank of the Rhône and 26 on the left hand bank. This gives a total of 211 km, more than two thirds of the total length of *bisses* in the Haut Valais (Aufdereggen and Werlen, 1993).

Bisses usually consist of a headwork structure, a principal conveyance channel, and secondary and tertiary distribution channels. In some cases the *bisse* may also supply storage reservoirs (*étangs*). Distribution of water from these channels can be by gravity (*ruissellement*) or under pressure (spray irrigation) often via an underground irrigation network (*réseau d'irrigation*). Risk strategies involved the construction of numerous channels down slope, thus taking advantage of different ecological niches and providing security in hostile environments. There is evidence for 10 *suonen* having been constructed at Mund (Jossen, 1989). At Grächen 4 *suonen* can be found within a drop of 150 m (Mariétan, 1952) and prior to 1937 there were three *suonen* only 50 and 150 m apart at Oberried (Bratt, 1995). These risk strategies have often had a striking impact on the local landscape (Crook and Jones, 1999).

What follows is a description of the design principles of the *bisse* system. This makes a distinction between traditional and modern techniques and illustrates the process of material and technical innovation and adaptation.

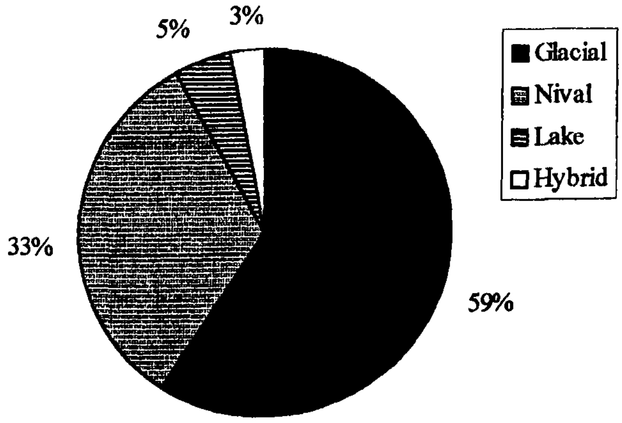

FIGURE 3. General *bisse* source characteristics. Source: Rauchenstein (1908); n=205.

BISSE WATER SUPPLIES

The *bisses* are slope off-take systems (Vincent, 1995) which divert water mainly from large seasonally variable yet predictable glacial meltwater rivers (e.g. 0.5–8 m^3s^{-1}), thus ensuring reliable discharge during the irrigation season (Figure 3). Nival streams and lakes are used where this option is not available, but these sources are prone to water shortage early in the irrigation season during low precipitation years (Reynard, 1995). Hybrid sources included the addition of surplus water from large *bisses*, torrents, small lakes, and snow fields. Multiple sources are commonly used in non-glacial *bisses* or long *bisses* (e.g. 5–32 km), which can cross watersheds. Each source has different flow and sedimentary characteristics, with implications for *bisse* design, construction, and management.

Prior to the late 19th century all *bisses* relied on gravitational flow to convey water. Since the beginning of the 20th century, there have been a few examples of *bisses* which receive water via motorized pumping, usually connected to hydro-electric power (HEP) installations (e.g. Bisse de Sillonin and Bisse de Briey) or from canals on the Rhône plain (e.g. Bisse Inférieur and Bisse Moyen at Leytron). The Grand Bisse de Lens has a hybrid system that incorporates both natural and pumped flow depending on river regulation. In most cases river discharges are regulated through HEP schemes.

Whilst irrigation is the principal use for this water, many *bisses* have historically supplied water to small scale industry, in particular grain and saw mills with water driven over-shot vertical wheels (Crook, 1997). Since the 1970s the abandonment of agricultural land has increased the fire risk on slopes. Some *bisses* (e.g. Undra suon) have been used in a precautionary role to irrigate vulnerable land, particularly next to railway lines, and others have been used on an emergency basis to put out forest fires (Crook and Jones, 1999).

THE CONVEYANCE SYSTEM

The head works of a *bisse*, known as the *prise d'eau*, diverts or traps water usually from a river at a convenient location. The location of many *prises d'eaux* at high altitude (600 m – 2,501 m) makes them prone to damage from slope, avalanche, and flood hazards. At the interface of the two environments (meltwater river and *bisse*), it can be crucial to reduce rapidly the erosional force of the water and prevent large debris from damaging the *bisse*. The *prise d'eau* can be anything from a simple dam to a sluice gate system containing a sediment trap (*dépotoir, désableur, désabloir*) and overflow facility (Figure 4). Some *prises d'eaux* are ephemeral and have been moved along river banks as hydrological characteristics have changed. As modern materials have been introduced, these structures have become more static and robust. The size of the structure and the materials used in construction reflect the durability of the *prise d'eau* and the erosional nature of the river. Concrete is the most favored construction material. The diversion angle tends to flatten as the velocity and erosional characteristics of the meltwater river increase (Figure 5; Crook, 1997).

In some locations (e.g. Grächen) water is captured at the head of the system by metal grids laid in the bed of the river. The water drops through the grid and into a *bisse*, from where it is distributed. Similar structures are used along the course of a *bisse* to trap water from tributary streams and supplement the *bisse* discharge. This water control strategy can have the advantage of stabilizing slopes. This theory is borne out by isolated examples of slope destabilization resulting from the abandonment of *bisses* (Crook and Jones, 1999). Only rarely will a principal *prise d'eau* capture the whole discharge (e.g. Gsponeri). In terms of watershed management, a 100% capture rate from any source is rarely desirable

FIGURE 4. A typical *prise d'eau* with sediment trap and overflow (Crook, 1997).

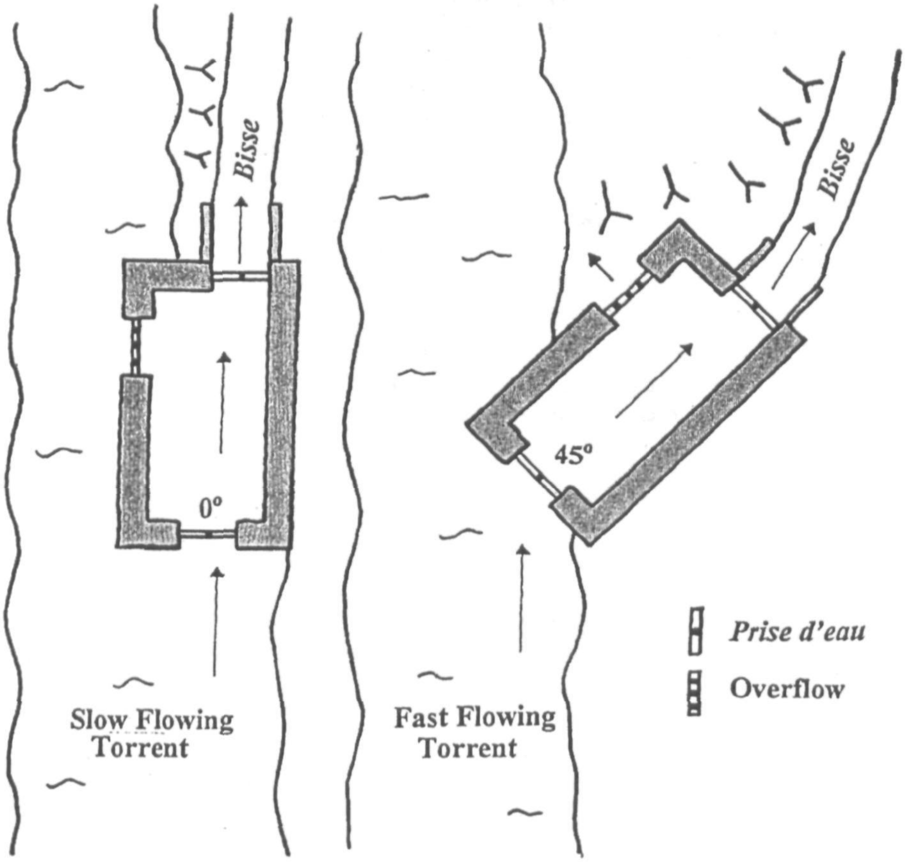

FIGURE 5. Diversion angles on typical *prise d'eau* (Crook, 1997).

for two reasons: *bisses* down slope require water, and a *bisse* capturing total discharge will be more vulnerable to seasonal climatic variation in supplies.

Sediment deposition occurs in all *bisses* as a result of their very low gradients and low velocities. These sediments are largely beneficial because they line and seal earthen channels; however, in some *bisses* the accumulation of fine sediment within a season inhibits the flow and so can be a problem. Additional sand traps may be placed along the course of a *bisse* which remove finer sediments with distance from the source.

Conveyance channels may be up to 32 km long and maintain low average slope percentages (Table 3) between the *prise d'eau* and end of the *bisse* (*exutoire*). Longer *bisses* required natural (e.g. waterfall/tributary stream) or artificial drops (e.g. sluice system/cascade). These were to maintain the flow through level terrain; reduce the number of barriers to a *bisse*, maintain a more manageable gradient; and to deliver water to land at different altitudes (e.g. Bisse de Levron, Bisse Vieux, Bisse de Saxon, Bisse de Zittoret, Bisse de Vercorin). The drop must be thoroughly regulated to ensure against erosional damage and bank rupture. Negotiating this terrain often involved traversing long distances and maintaining slope angles of between 1° and 5° to prevent excessive sedimentation or fluvial erosion (Chavan, 1915). Depending on the terrain, the drop in altitude between the source headworks and the irrigated area may be large (4 m–>1,500 m), although the principle of constructing a number of *bisses* down a slope limited this drop in altitude in most cases.

TABLE 3
Average slope angle of bisses

Average slope %	No. of *bisses*	Average slope %	No. of *bisses*
< 1	10	7–7.9	9
1–1.9	20	8–8.9	4
2–2.9	23	9–9.9	5
3–3.9	14	10–14.9	13
4–4.9	12	15–19.9	4
5–5.9	10	20–30	4
6–6.9	6	> 30	1

(NB: based on Reynard's data *in* Bratt, 1995)

There were also "social" hazards which affected the routing of a *bisse* such as the Girlfriend's Step, *"le pas de la matta."* This refers to the alleged tendency of a *bisse* engineer to route a *bisse* above his girlfriend's fields for sexual favors, but avoiding the fields if the girl would not consent (Bratt, 1995).

Principal channel widths range from 0.3 to 1.5 m and depths range from 0.2 to 0.8 m. The average channel cross-sectional dimension, which provides an indication of the overall channel capacity, is 0.26 m^2 (Crook, 1997). Most channels present a large surface area which encourages warming of the water over long conveyance distances. Modernization usually increases principal channel capacities (e.g. Bisse de Savièse), with the largest channels around 0.48–0.8 m^2. A typology of slope channels, channel materials, and channel morphology has been produced which relates to the permeability of the substrate and geomorphic hazards (Table 4). In many communes, *bisse* channels were earthen cut, using hand tools since this was the cheapest and easiest method of construction. Contemporary earthen channels are sometimes cut by machines, for example at Täsch in the Mattertal. Originally, most *bisses* had open channels. These present advantages and disadvantages to farmers

- Advantages: Warms the water, cheap and easy construction option.
- Disadvantages: Evaporation, theft/damage easy, and requires regular cleaning and maintenance.

Excavation debris from construction and maintenance is used to reinforce the outer bank and provide a walkway known as a *banquette* or *tretschbord*. In some loca-

TABLE 4
A bisse *channel typology on flat or gently sloping terrain*

P*	Type	Sub-Type	Materials	Morphology	Sealants
Low	Excavation	Unlined	earth	rectangular, trapezoidal, square	silt, moss, vegetation
		Lined/Hybrid	stone, wood–planed or poles concrete, corrugated iron, masonry		
High	Artificial	Surface	wood–single trunk or joined composite, galvanised metal, aluminium, concrete, PVC, masonry or tresselled	rectangular, trapezoidal, square, semi-circular, crescent, circular	resin, cloth, moss polythene, wood
		Subterranean	galvanised metal, aluminum, concrete, PVC, masonry	circular	resin, vegetation

P* = Substrate permeability. Source: Crook, 1997.

tions, such as the Bisse de Vercorin, the banquettes have built up approximately 2 m above the bed of the *bisse*. Vegetation plays an important role in binding together and strengthening *banquettes* particularly along rock cut sections, where it improves the adherence to the substrate and prevents erosion and rupture of banks. Collapsing *banquettes* can be a problem, either as a result of slope movement, tree roots breaking the bank, or trampling from cattle or people. In areas where damage was common, the channel was often shored up with wooden poles and other materials, or was protected by a wooden cover (*ploton*) (Bratt, 1995).

Artificial channels are needed in unstable and permeable areas. When a *bisse* has to traverse undulating or unstable ground, it is often placed on supports that can be made from any durable material. Supported sections often incorporate wooden wedges (*cheville*) to cope with periodic slope movement caused by landslides and seismic activity. Water is conveyed across bridges where the terrain is dissected by deeply incised river gorges. This avoids damage to the channel, maintains an efficient gradient, and has the benefit of shortening the conveyance system (Rauchenstein, 1908).

Most early artificial channels were wooden. Many wooden channels were replaced at the turn of the 20th century by galvanized metal, masonry, and concrete channels (Michelet, 1995). In turn, cheaper and easily transportable materials, such as PVC, have replaced many of these materials. Wood has regained favor in recent years as it creates aesthetically desirable landscapes which are important to the tourist industry. It is not uncommon to find examples of many of these materials along a single *bisse* (e.g. Grand Bisse de Salins).

In some locations, particularly at the head of hanging valleys in the Bernese Alps on the northern slopes of the Rhône Valley, the terrain is rocky and vertical. Glacier- and snowmelt-fed rivers cascade down into the Rhône River, whilst in contrast the adret slopes at the heads of these valleys are some of the most arid in the Valais. Diverting water to these areas meant that the inhospitable terrain could not be avoided (*passages obligatoires*) and, therefore, had to be overcome (Bratt, 1995). The methods by which these problems have been overcome have led to the creation of some of the most impressive and famous *bisse* structures, such as the Bisse de Savièse (Figure 6) and Bisse de Roh (Mariétan, 1934; 1948). The strength, tenacity, and organization required to build and maintain these structures have gone a long way to establishing a *bisse* culture.

Four methods have been commonly used in these situations: carving out a channel from the rock, tunneling, bridging, and wooden constructed channels fixed to the rock face (Table 5).

Artificial conduits are characterized by their regular maintenance and often need replacement. Larch was the favored channel material because of its low permeability and local availability. Other woods, such as pine and spruce, were used as supports. The average lifespan of larch components was 20–30 years, with some sections lasting much longer. Channels were sealed with locally available materials, such as moss and natural resins.

Techniques for cutting rock have evolved from hand cutting, to the use of explosives and hand finishing, and finally just blasting (Högl, 1995). Högl (1995) identified six chronological phases of channel construction on the Aqueduc de Sils (Grisons canton). Channel development moved from a simple supported wooden channel (medieval), to a rock cut platform with a wooden channel (at times supported) (up to the late 1600s) and then to a new source and a suspended wooden bridge. Suspended channels must have enough strength to withstand large forces from both gravity and the weight of the water-filled channel. Counterbalancing techniques evolved with an understanding of the forces and stresses involved in supporting a wooden channel (Högl, 1995). Initial channel construction required major labor-intensive excavation. A less labor- and resource- intensive process of construction was later developed and refined. This maintained strength and increased the size of channel that could be conveyed (Figure 7).

Högl (1995) also identified many different designs of *boutzets* (wooden beam) and *boutzesse* (hole cut for the wooden beam, Figure 7) which evolved to support or suspend large artificial *Chänils*. These were either supported by poles (A), incorporated *cheville* (C, D, and E) or natural (B) and artificial (F) hooking devices to increase channel stability and spread the load. The metal spike used in *Boutzesse* F is only found in the Grisons canton.

Moving materials into these dangerous locations sometimes presented logistical problems. For this reason, communal forests were reserved for the building and maintenance of *bisses*. On the Bisse de Savièse a small saw-mill was established along the suspended section to alleviate the problem of transporting large pieces of timber (Paris and Seylaz, 1988). Avalanche and rockfall damage was so predictable along this *bisse* that sections of conduit, the *Paroi du Sapin* and *Paroi des Branlires*, were removed and stored in winter (Franzoni, 1894). Large sluice gates (*déchargeoir*) were placed at the beginning of dangerous sections to divert water out of the channel allowing maintenance and to alleviate problems of rupture, particularly during or after large precipitation or melt events.

In the evolutionary process, many rock cut channels and suspended wooden sections have been replaced by rock cut tunnels to avoid avalanche or rockfall damage, increase discharge capacity, or replace exceptionally dangerous sections. Excellent examples of tunnels can be seen at Mund, Eggerberg, and Ausserberg. Tunnels are often shored up with wood, masonry, or concrete in zones of weakness. Longer tunnels occasionally had windows cut into the rock, for example at Savièse and Ayent (Ruchenstein, 1937; Bratt, 1995). These tunnels required larger dimensions to prevent collapse. Recently constructed tunnels are often sprayed with concrete as reinforcement. Many modern tunnels have a dual function, conveying both drinking water (piped) and irrigation water (open conduit) to a commune; for example, the Bisse Roh tunnel at Crans and Niwärch/Mittla tunnel at Ausserberg.

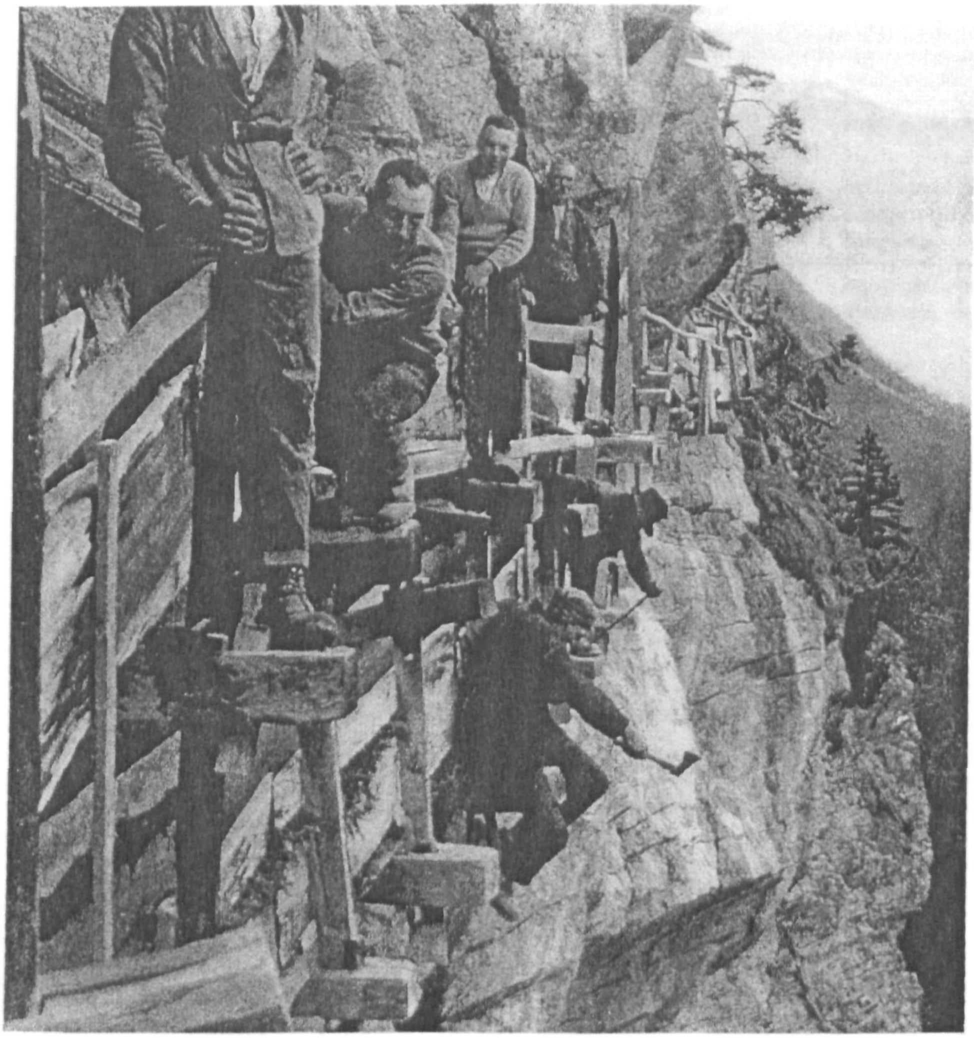

Figure 6a. Bisse de Savièse (Paris, 1948, in Mariétan, 1948).

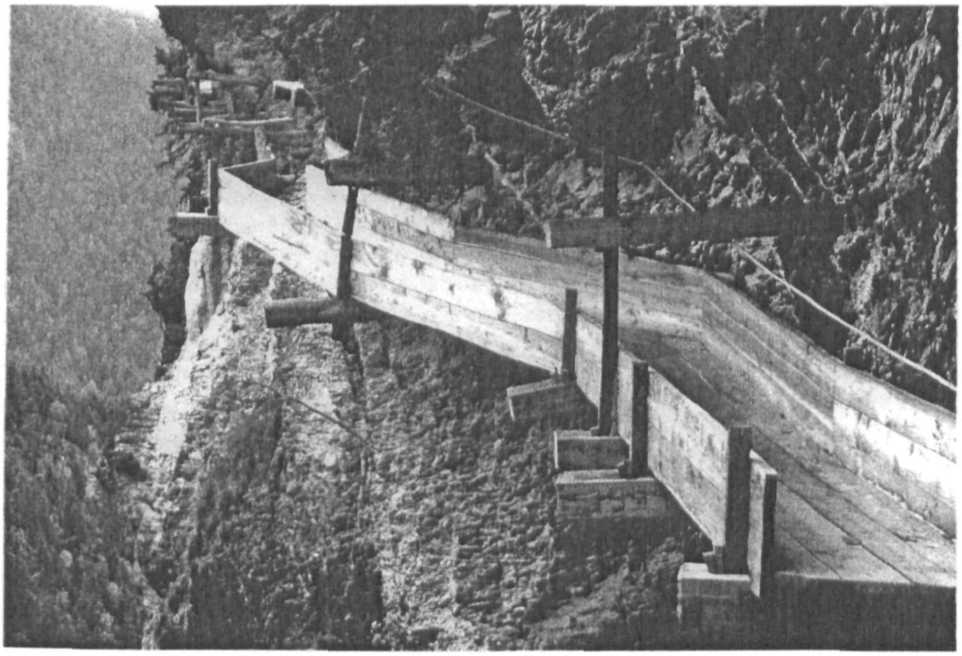

Figure 6b. Reconstruction of the wooden channel in the Bisse d'Argent (Crook, 1997).

TABLE 5

Methods of conveyance through vertical, near vertical, dissected or undulating terrain

Method	Sub-Type	Materials	Techniques	Typical Dimensions
Rock Cutting	Whole channel	non-permeable rock	hand pick, hammer	Depth 0.2–0.3 m Width 0.2–0.5 m
	Hybrid artificial	non-permeable rock, stone, earth, masonry	orthostatic plates and earthen fill or masonry *banquette*	Depth 0.3–0.45 m Width 0.3–0.6 m
Tunneling	With surveillance path	wooden support joists, artificial channel along the tunnel floor sprayed concrete wall supports	hand pick, hammer, dynamite, drilling	Depth 0.25–0.45 m Width 0.4–0.6 m Length 5–3,000 m
	No surveillance path			Depth 0.25–0.4 m Width 0.25–0.6 m Length 1–2,000 m
Artificial Conduit *chänile, bazot, brozets brochets, chénaux, tsénas, kennel*	Suspended Cantilevered	wood (larch canal and pine support) single trunk or joined composite, metal or plastic	wooden channels (*krapfen*) attached to *boutzets* or *encorbellements* supported by *co-outacoué (étau, gétos)*, placed into holes (*boutzesse*) chiselled out by a man counterbalanced on a plank or suspended on a rope	Depth 0.25–0.4 m Width 0.25–0.4 m (single trunk) Depth 0.3–0.45 m Width 0.3–0.45 m
	Supported	wood, metal or PVC		
	Bridging	wooden trunk or joined composite (*tséna, tsénei*), metal, PVC masonry, concrete	single span or supported with or without a walkway (*passerelle*). wooden wedges (*cheville*) are often required to level the channel	Depth 0.2–0.45 m Width 0.25–0.45 m

Source: Crook, 1997.

The *bisse* inventory describes 47 of 136 *bisses* (with available data) as having some form of cover, piping, or tunneling (Aufdereggen and Werlen, 1993). The average length of this cover is 2,036 m but ranges from 50 to 10,700 m with a mode of 1,000 m. From observation, the numbers of *bisses* with some form of covering is probably much larger.

OPERATIONAL DISCHARGE LEVELS

Many *bisses* were seen to operate at much lower discharges than the maximum possible (e.g. Bisse Milieu and Bisse Dessous at Nendaz), partially because of wet conditions in the survey years 1995 and 1996, but this also reflects a built-in over-specification in channel design. This design principle allows the capacity of *bisses* to be increased in drier conditions and also prevents excessive erosion occurring. Weekly discharge (1995 irrigation season) ranged from 0.001 m^3s^{-1} to 0.29 m^3s^{-1} in nine *bisses* (Bisses Vieux, Milieu, Dessous [Nendaz]; Zittoret, Lens, Sillonin [Lens plateau]; Niwärch, Undra, Wiingartneri [Baltschiedertal]) with most lying between 0.067 m^3s^{-1} (25th percentile) and 0.136 m^3s^{-1} (75th percentile) (Crook, 1997).

The transfer of water through the conveyance network can lead to considerable losses of water, estimated at between 25% and 75%, because of infiltration, leakage, and evaporation (Michelet, 1995). Further large losses can occur in the secondary and tertiary distribution networks (e.g. 38% at Chermignon–Crook, 1997). The settlement of sediment in channels reduces this impact. This is confirmed by the low infiltration rates (0.02–1.6 mm h^{-1}) in these zones (Crook, 1997).

A number of communes, particularly on the south-facing plateau of the north Rhône slopes, have storage ponds (*étangs*) that collect water during days when a *bisse* is not in use. Those of Savièse, Ayent, and Lens are glacial in origin; however, other *étangs*, such as at Illsee (1623), were artificially constructed to capture snowmelt (Mariétan, 1948).

WATER DIVISION

Water rights are attached to different sectors (known as *tassets* or *tours*) of an irrigated area. It is necessary to divide water, according to the allocation of each sector, throughout the conveyance system. Water is also divided up within each sector into secondary and tertiary canals. The general characteristics and methods of water division are illustrated in Table 6.

Division of water (*répartition*) in the main conduit was traditionally achieved with a *répartiteur* or *grand-partiteur* (Figure 8). A *répartiteur* is a sluice system which divides water equitably between different zones of a commune or different communes. The division follows statutory agreements which are normally fixed by time or

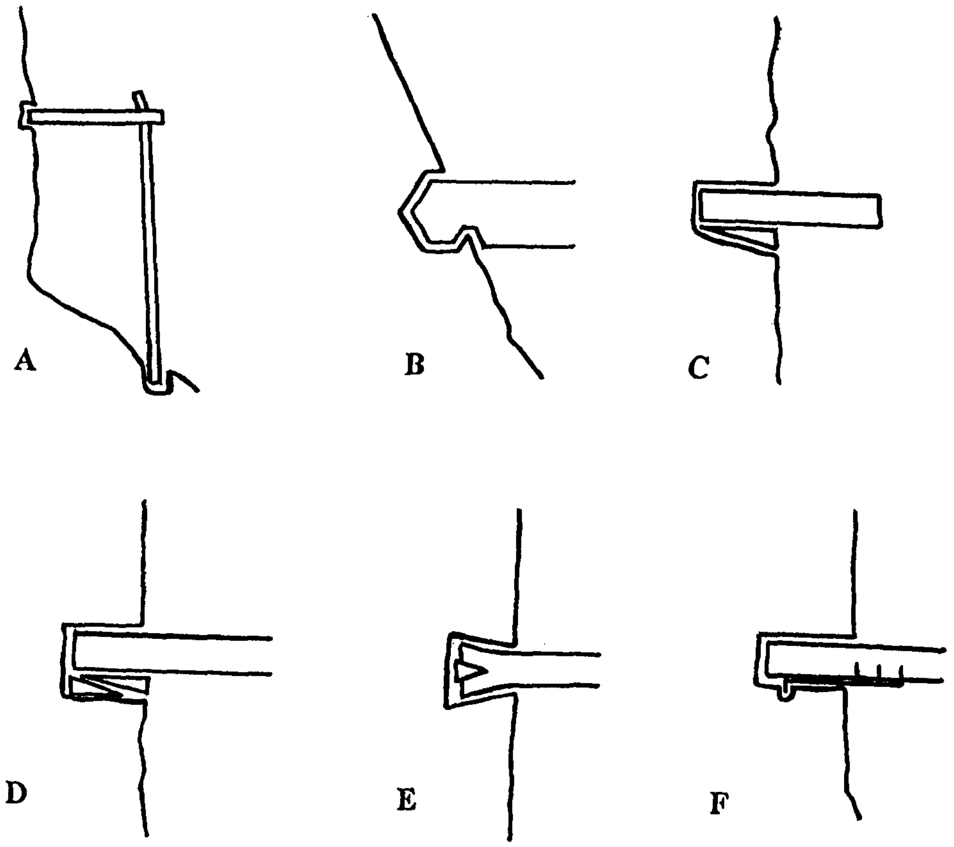

FIGURE 7. *Boutzets* and *boutzesse* (After Högl, 1995).

TABLE 6

General characteristics of water division along a conveyance system

	Method of division		
	Répartiteur	*Grand-partiteur* *partichiou* or *diviser*	*Plaques, étanches,* *kusi tonieu* or *tornieu*
Channel Type	Primary & secondary channels	Primary canals	Secondary & tertiary channels (*raye* or *rigole*)
Percentage Division	Proportional or total	Proportional	Total or proportional (used in unison with other *plaques*)
Flexibility in Division	Fixed or adjustable (sluice system)	Fixed or adjustable (sluice system)	Fixed
Material	Wooden, concrete, metal drum	Earthen, concrete, wooden	Stone, wood, metal, earth sod
Divider	Guard or *répartiteur* on the primary canal, individual on secondary canal	Guard or *répartiteur*	Individual farmer
Name of Division	*Bulletin, Erzeret or Droit*		

Source: Crook, 1997.

amount, although there is flexibility in this division. The whole flow passes through the *répartiteur* from where water is divided between pre-calibrated sluice gates or wooden holes (Netting, 1966). Original *répartiteurs* were wooden, whereas modern forms are usually made from concrete. A *répartiteur* can also function as an overflow system, redirecting excess water into nearby torrents and sediment traps. A *grand-partiteur* tends to be a less substantial structure than a *répartiteur*, but they are now frequently made from concrete. A *grand-partiteur* divides water in the principal channel in a fixed quantity: there is generally less flexibility in this division although sluice gates can be used to block either side of the *grand-partiteur*. There are two main types of sluice gate used within a *bisse* system: non-adjustable sluices that operate either open or closed, or adjustable sluices that divide a vari-

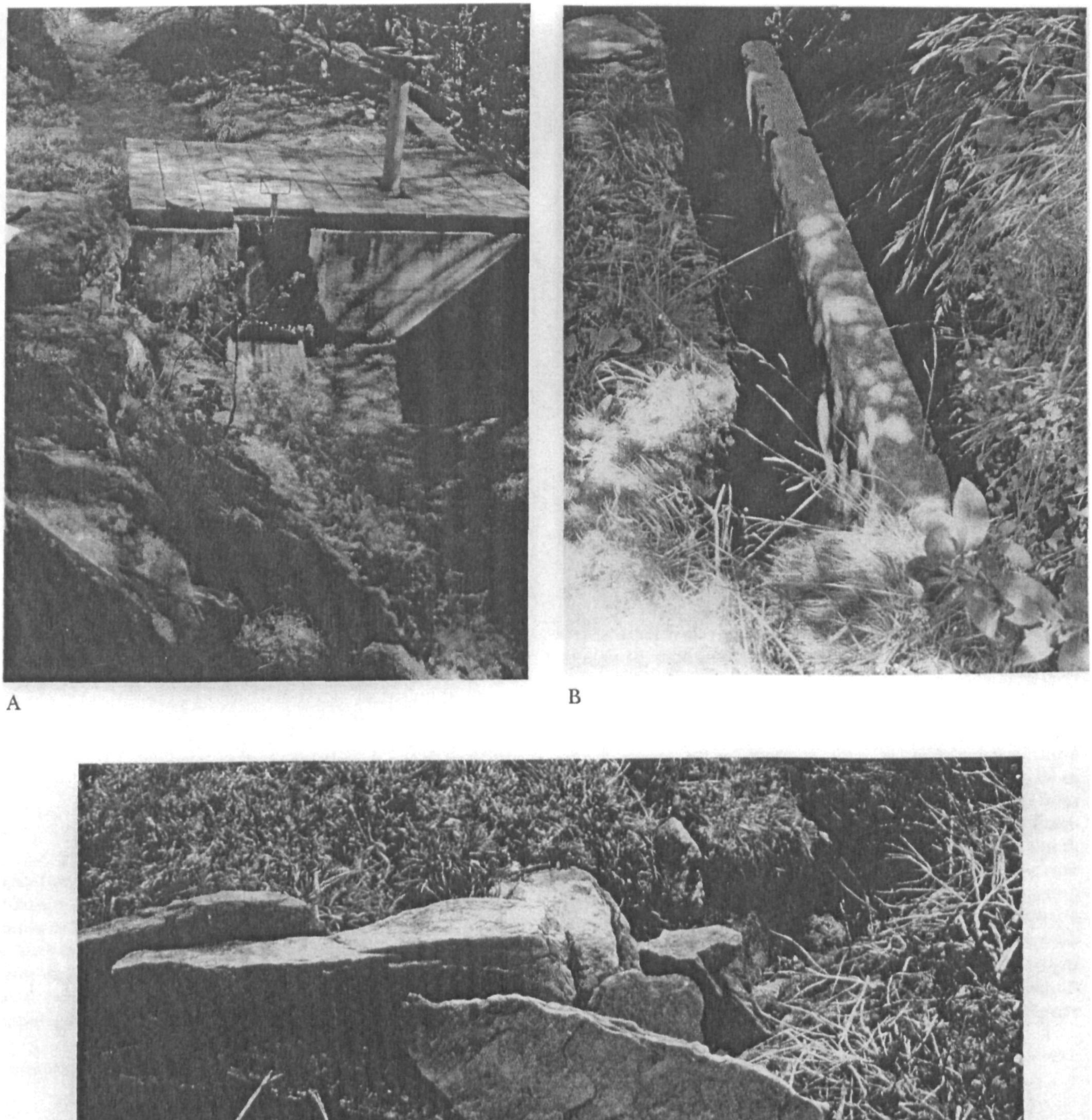

FIGURE 8. A: *Répartiteur;* B: *partichiou,* and C: *étanche* (Crook, 1997).

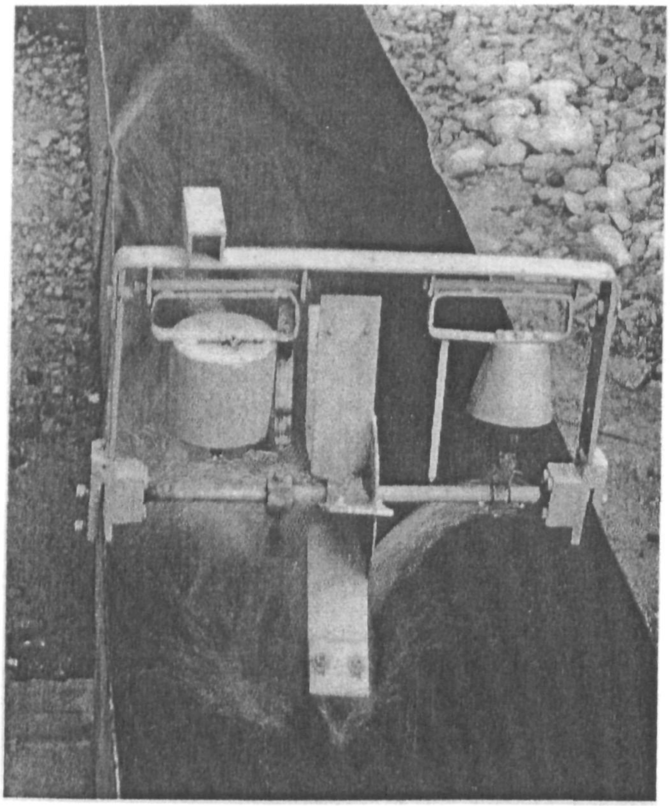

FIGURE 9. A *martinet* on the Grand *Bisse* de Vercorin (Crook, 1997).

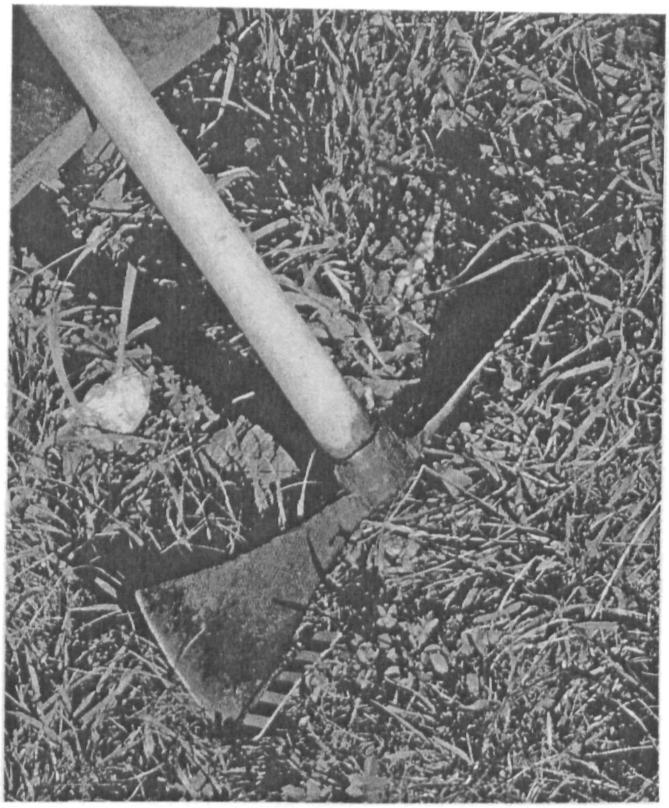

FIGURE 10. A *délabre* (Crook, 1997).

able amount of water, thus providing more flexibility. Traditionally, wood and stone sluice gates (*écluse, enclorse, celluse*) were used; more recently these have been replaced by galvanized iron or aluminum sluice gates. Sluice gates can be used to divide, distribute (*destournyour* or *détournoir*), or discharge water (*déchargeoir*). *Plaques* or *étanches* aid distribution through the secondary and tertiary networks and are also used in the distribution process. The *étanche* (*kusi, plaque d'arrosage, tranchant, torieu, torgnoü, Wasserplatte*) is a more mobile and versatile divisive tool usually made of metal but sometimes of wood or stone (Figure 8).

In places, *bisse* guards used a simple but effective water-driven (usually wooden) wheel placed in the *bisse* which struck a hammer against a metal plate making a noise to monitor flow. The size of this wheel varies from around 0.25–1 m in diameter. This instrument was known as a *marteaux, baratte, roue à palettes, Kontrolhammer, Merkhammer,* or *Wasserhammer.* If the noise stopped, the guard would be aware that blockages or damage may have occurred. He was then responsible for investigating the reasons for this disruption to the supply and taking immediate remedial action. This practice is almost universally redundant although a number of consortages and communes maintain these structures for tourism. A smaller version of a *marteaux* is called a *martinet* (Figure 9).

WATER DISTRIBUTION

There are two main methods of water distribution associated with *bisse* irrigation: traditional *ruissellement* and spray irrigation. The latter is often used in conjunction with an irrigation network (*réseau d'irrigation*) although it may be operated on a mobile basis.

RUISSELLEMENT

Ruissellement is a form of border irrigation. The traditional distribution of water from *bisses* is normally carried out from a secondary or tertiary channel (*kapiou, kusi, rigole, levoir, moneresse, trazoé, tsaseila, erzère, bedarra, viou*) and less often from the main canal (*tora, trasoir, traysiour, raie, coursière*). Tertiary channels vary in length from about 1–100 m depending on field size. The responsibility for distribution can fall on either the farmer (*consort*) or an elected official (e.g. *garde, ardjou, (g)erdiou, arzieu, azieu, erdjiou, erzyu, erwin, ewin*); however, where the topography is favorable, distribution can be left completely unsupervised for long periods (2–3 hours) (Crook, 1997). The water is either diverted through a sluice or the channel is dammed with a piece of wood, metal, or stone (*étanche*) so that water overflows the banks of the *rigole*. Alternatively a sod of earth may be cut in the channel sides using a special tool known as a *délabre* (Figure 10) or a broad-bladed pick axe (*pioche* or *Wässerhaue*), thus breaching the channel temporarily. Water washes through the side of the channel and flows down slope. This will continue until the required area is flooded. At this point, the *étanche* is removed and placed further along the distributary channel allowing the irrigation of another section of the field (Figure 11). Thus, the bed of the *rigole* must be at a height to assist gravitational flow onto the land and the *rigole* must be large enough to supply sufficient water to reach the end of the run in the desired time and be small enough as to be non-erosive.

As the water flows over the ground the farmer often uses an *étanche, délabre, pioche,* or spiked tool to aid distribution and infiltration. Ideally *ruissellement* should not create extensive flooding or involve large tail (drainage) losses, although overland runoff and drainage can be rapid (e.g. a site in Chermignon had tail losses amounting to 38% of the total water delivered–Crook, 1997). Small tail losses, however, are important because they flush out of the field any salts left from the last irrigation. In the view of the authors small tail losses have been one reason why the *bisses* have been sustainable. A number of plots may be irrigated simultaneously from the same *bisse* or from different *bisses* according to the system of turns (*tours*). The uniformity of the distribution process is often poor (Crook, 1997), which over time has promoted diversity in the flora of the fields (Werner, 1995). Thus, these fields have importance for the tourist industry. Hay and orchard crops are robust and resilient to *ruissellement* distribution techniques.

The interval between meadow irrigations by *ruissellement* is a product of irrigation management rather than demand or considered intervals. Loup (1965) reported that irrigated meadows received 3–8 irrigations over a 3–6 month period, with 2–3 irrigations before the first hay crop and a similar number before the second hay crop. Irrigation normally commences in June, but in very warm and dry years pre-irrigation may be required in April. There are a number of different estimates of how much water is required; this is dependent on a number of factors including the antecedent soil moisture conditions, soil texture (infiltration rate) and the given crop and crop development phase (Crook, 1997).

Muller (1946) determined that a hay meadow irrigated by *ruissellement* requires 2,000 m^3 ha^{-1} received at an approximate constant discharge of 2 l s^{-1} ha^{-1} (Muller, 1955). Huber (n.d.) calculated that a 400 m^2 meadow at Chamoson required a discharge of 30 l s^{-1} for 50–60 minutes giving a total of 2,250–2,700 m^3 ha^{-1}. Michelet (1995) said that effective meadow irrigation by *ruissellement* requires water supplied at a rate of 1.5 l $s^{-1}ha^{-1}$. Muller (1946) found that, in the central Valais region, the water needs during the growing season for hay meadows were approximately 10,000 to 12,000 m^3 ha^{-1}. More recent estimates of irrigation requirements in Sion are that 2.3–3 mm of water a day must be supplied (Reynard, 1995). During an irrigation event at Chermignon the distribution canal had a discharge of 96 l s^{-1}, which is much higher than the other figures (Crook, 1997). In general, irrigated lower meadows (below the *mayen*) produce four harvests and *mayens* two harvests (Michelet, *pers. comm.*, 1994). Irrigated *mayens* just below the alp serve as pasture twice yearly and receive one cut in the autumn. A more liberal assessment of the benefits of *mayen* irrigation is presented by the consortage of the Bisse de Vercorin who quote a 30% increase in the second harvest (Perraudin Kalbermatter and Marin, 1995). In all examples, irrigation results in a site specific improvement in both the quality and quantity of the harvest. After the final cut, meadows are used for cattle grazing.

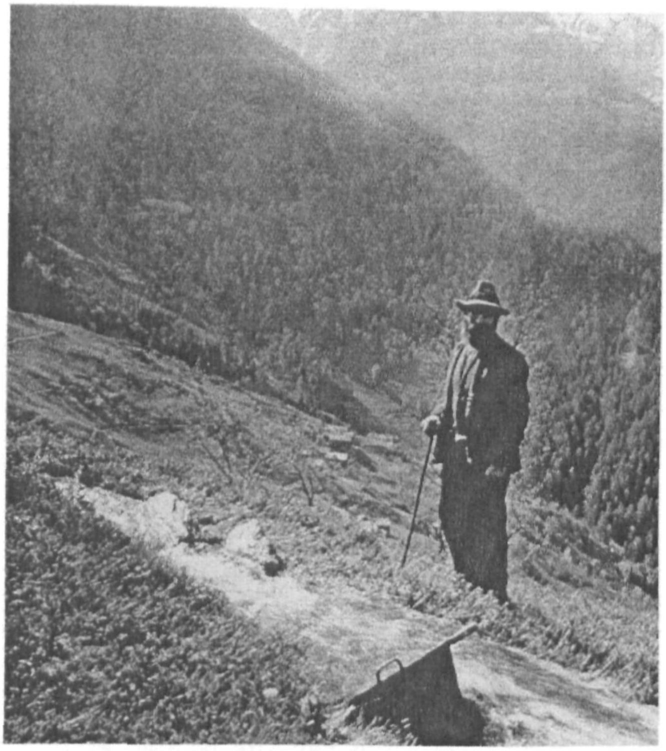

FIGURE 11. The *ruissellement* technique (Paris, 1948), in Mariétan, 1948.

On the alp (2,000–2,600 m), rainfall is generally sufficient to allow vegetative growth and hence it is not absolutely necessary to irrigate. The intensive exploitation of the alp, however, is dependent on adding nutrients to the soil in a process known as ferti-irrigation, or chemigation (Logan, 1990; Viérin, 1995; Roulier, 1995). This occurs approximately every three years on the impoverished soils of the crystalline regions of the Pennine Alps, Aar Massif, and Lépotitiennes. Manure, known as *'lisier,'* stockpiled during the stabling period, requires dilution before diversion into numerous small channels (*rigoles*) from where it overflows. The required ratio of *lisier* to water is usually 10:50 for each irrigation (Viérin, 1995). Periodically, artificial fertilizers are also used.

Vineyards irrigated by *ruissellement* required 0.5 m to 0.8 m infiltration per irrigation in every other row, which took from 12 to 24 hours (OFA, 1973; Lampert, 1978). These required two or three irrigations a year with a three to four week gap between irrigations. It is approximately 20 years since *ruissellement* was regularly used on vines in most regions (OFA, 1973; Barras, *pers. comm.*, 1995).

Ruissellement is also used to irrigate meadows and orchards on the Rhône plain from *meunières*. In particular apricots are irrigated in this way, because too much water on the apricot fruit leads to rotting (Nançoz, *pers. comm.*, 1994). The *meunière* is usually much larger and deeper than a *rigole* and raised slightly above the level of the flat basin. This allows flooding by blocking the channel in sections in much the same way as on a slope. Larger quantities of water are applied to these fields because of their sandy soils and the dry conditions (Muller, 1946). Plain irrigation is dependent on efficient drainage. Sufficient quantities of water have to be administered to leach any build up of salts. Traditionally, sediments cleared each year from the *meunières de colmatage* (now abandoned) of Martigny were used to build up the growing medium on the Rhône plain, preventing rapid infiltration and helping to maintain soil fertility (Commune de Martigny, 1992).

SPRAY IRRIGATION

Spray irrigation, which became available at the start of the 20th century, was introduced as a more economic (in terms of cost and water savings) distribution method than *ruissellement* (Loup, 1965). Besides this, the flattened terraces favored for commercial vine production made *ruissellement* difficult. Since the 1930s, numerous communes, with the financial assistance of the Service des améliorations foncières (SAF) (Agricultural Laws dated 1917, 1937, 1951, and 1961) in a process of intensification, rationalization, modernization, and land consolidation (*remainement parcellaire*) have constructed spray irrigation networks (*réseau d'irrigation*) (Loup, 1965; Roduit, 1979). Also, around this time, many vineyards were restructured, mechanized, and improved by irrigation. The widespread introduction of spray irrigation facilitated the cultivation of speculative crops, such as strawberries, blackcurrents, raspberries, and numerous vegetable crops in the Rhône valley and adjacent slopes of the Bas and Central Valais. Thus, these adaptations have only occurred in areas where economically sustainable livelihoods can be maintained with agriculture providing the principal source of household income (Crook, 1997).

Numerous *bisses* were adapted to meet the changing water demands of new commercially grown crops. This was often a process which involved both physical and institutional change. Physical adjustments included gradually abandoning direct distribution onto meadows from the main channel and concentrating on the delivery of water to communal reservoirs (*étangs*), small private tanks, and cisterns from where it is distributed, after storage. This water is often divided through a series of underground pipes or spaced laterals to fixed hoses located in different sectors of an irrigation grid (*réseau d'irrigation*). Like *bisses*, water distribution is carried out in rotation to different zones by opening and closing valves or sluices in the network. Alternatively water is diverted direct from a *bisse* via a small hose pipe to a mobile rose. This method is normally used in conjunction with traditional methods to distribute water to sections of a meadow where *ruissellement* is difficult.

Spray irrigation never requires a pressure of more than two atmospheres, which can be obtained from a 20 m drop. The sloping land of the Valais produces a large natural pressure gradient that often requires reduction and regulation to ensure a uniform distribution of water. Pressure can be reduced by using smaller pipes to distribute the water (e.g. Nendaz) or pooling the water in intermediary reservoirs, as on the Mittla Suon network (Crook, 1997). Pumping is required solely on the Rhône plain. The delivery of water is managed to ensure an adequate supply during peak demand. Individually, each irrigator may face restrictions on the number of hoses used at any one time. The size of roses (*robinets*) is also frequently standardized, often in line with the communal fire regulations or irrigation controls in built up areas and in the periphery of these zones (e.g. *bisses* of Zacrettaz and Villa). The size of the rose will influence the spray length and therefore the spacing between and along laterals. At Ausserberg, a central *réseau d'irrigation* can be joined by individuals who supply their own spray irrigation roses (Ordal, *pers. comm.*, 1995). A consortage (*Geteilschaft*) charges individuals to install robinets onto the main *réseau d'irrigation* (subsidized by the commune or *Gemeinde*) (Ordal, *pers. comm.*, 1995). The Niwärch suon has a north sector reservoir and Mittla suon an east and west sector reservoir to supply these spray irrigation networks.

In general, spray irrigation permits more simultaneous use than *ruissellement*, which is important as the introduction of commercial monocultures meant that the timing of irrigations frequently coincided. Valaisan vines are generally irrigated twice in a year, but extreme weather may change these requirements to one or three irrigations. Each irrigation lasts either 12, 16, or 24 hours (Muller, 1946) depending on the capacity of the rose and antecedent soil moisture conditions. For effective spray irrigation, a *bisse* must have a constant discharge of 0.5 to 0.8 $\mathrm{l\ s^{-1}\ ha^{-1}}$ (Michelet, 1995). Whilst wet years can produce poor harvests, many irrigators are reluctant to miss irrigation turns, often to the detriment of the crop (Barras, *pers. comm.*, 1995).

DISCUSSION

The users of the *bisses* have adapted to periods of continuity and change by integrating modern technological innovations and materials when and where appropriate. This discussion attempts to put these changes into a wider context through comparison with other irrigation systems. It also provides a critique of some of the more recent changes associated with new distribution techniques.

The successful design criteria of *bisses* were matched to the unique and often harsh environmental conditions found in different communes. Whilst flexibility in design was crucial, similarities do exist. Engineers have been highly ingenious at adapting simple techniques to overcome specific obstacles.

The individual status of each *bisse* system is determined by water availability. The *bisse* system, like ancient Peruvian systems (e.g. Jun.–Dec. 4 $m^3 s^{-1}$, Jan.–May, 10–34 $m^3 s^{-1}$: Farrington and Park, 1978) and modern Chilean systems (e.g. approximately 0.3-80 $m^3 s^{-1}$: Gwynne and Meneses, 1994), are characterized by partial diversion from large seasonally variable but predictable glacial meltwater rivers. For example, monthly discharge at Châble in the Val de Bages (1962–1988) varied from 0.5 m^3s^{-1}, the minimum figure in January, to 8 m^3s^{-1}, the maximum figure in June (Luyet, 1990). This provides abundant good quality water. This is in stark contrast to the total diversion used in the Levada system of Santo Antao which captures much smaller, ephemeral, and unpredictable stream discharges (0.5–1 $l s^{-1}$: Haagsma, 1995).

Gradually, over time, communes and *consortages* have improved water security by seeking more reliable glacial meltwater sources or by constructing *étangs* and small reservoirs associated with spray irrigation. This latter strategy is also used in irrigation systems where there is a shortage of water and unpredictable supplies, such as in Cape Verde (Haagsma, 1995), the Maltese islands (Jones and Hunt, 1994), and Portugal (O'Neill, 1987). Combination systems have sometimes arisen as a result of the evolutionary nature of irrigation, as people and their institutions adapted to new socioeconomic, demographic, technical, and environmental conditions. These incorporate multiple sources including springs, streams, and meltwaters, particularly where there is no glacial meltwater source or long watersheds to cross. Similar multiple source strategies are found in Kenyan and Tanzanian slope off-take systems (Adams *et al.*, 1994). The complex nature of water allocation along slopes has produced hydrologically bizarre scenarios where *bisses* cross each other or large torrents bypass *bisse* conduits, each source having its own institutional or individual arrangements. This is possibly a result of the extensive and plentiful water supplies in the Valais, as in areas where water is more scarce, such as the Maltese islands, the institutional boundaries are simpler (Jones *et al.*, 1998) although organization may be complex (Adams *et al.*, 1997).

Risk is spread through the system by constructing channels at different altitudes. The *prise d'eau* of *bisses* (496 m–2,600 m) have a greater distribution, and therefore spread of risk, at altitude than the Levada of Santo Antao (700–800 m: Haagsma, 1995) and Madeira (about 500–1,600 m: York, 1992), and irrigation systems in Marakwet, Kenya (c. 1,400 m; Adams *et al.*, 1997), Tarakot, Nepal (3,000 m: Werner, 1995), Bolivia and Peru (3–4,000 m) (Campbell and Godoy ,1986; Gelles, 1994), and parts of Ecuador (> 2,500 m: Vincent, 1995). These differences in altitude, however, are partly explained by the large altitude range in the Valaisan landscape in comparison to the other regions.

Channel morphology varies but is characteristically trapezoidal or semi-circular when open, and circular when enclosed or buried, as is often the case after modernization. The local topography is largely responsible for restricting the standard dimensions of principal *bisse* channels as in the Levada on Santo Antao (0.2 × 0.2 m: Haagsma, 1995), Madeira (York, 1992), and Cusichaca, Peru (Bowen, 1995). Thus, *bisse* channel dimensions are much smaller and systems shorter than the cross sections (2 m × 1–1.5 m) and length (28–79 km) of those recorded for ancient inter-valley irrigation canals in the Moche Valley of Peru (Farrington and Park, 1978). *Bisses*, however, are longer than the majority of Madeiran and Cape Verde Levada systems (250 m–7 km; Haagsma, 1995) and similar in length to the furrow systems in Marakwet, Kenya (up to 14 km; Adams *et al.*, 1997).

Discharge levels reflect a built-in over-specification in channel design which allows the capacity of *bisses* to be increased in drier conditions and prevents excessive erosion. The latter reason is a characteristic of over-specification in Andean systems (Farrington and Park, 1978). Excess water can be re-diverted into streams and rivers and thereby used in other systems, often informally. This is a hydrological strategy seen in many other indigenous technology irrigation systems, such as the Balinese Subak (Geertz, 1972), Cape Verde Levada (Haagsma, 1995), Maltese well and cistern systems (Jones and Hunt, 1994), and Libyan floodwater farming systems (Gilbertson *et al.*, 1984; Gilbertson and Hunt, 1995). Furthermore, the discharge in glacial meltwater streams is far more predictable, reliable, and secure than the rain-fed systems of Santo Antao (Haagsma, 1995), which suffer greater inter-system variation (intervals of 20–75 days in different systems) in water supplies.

New competition for water from hydro-electric power companies has been successfully buffered by negotiating with the companies, a factor also in the development of the Levada dos Tornos in Madeira (York, 1992). This has served to secure rather than threaten water supplies (Crook, 1997). Increasing domestic and tourist demands for water at present do not threaten the *bisses* as these water supplies have different sources. This contrasts with the situation in Cape Verde in which water supplies are so scarce that competing water users threaten the irrigation system (Haagsma, 1995).

Slope conveyance is remarkably efficient, considering the physical obstacles placed in the way of *bisse* constructors, with 85% of *bisses* having average slope percentages of less than 10% and generally lower gradients (0–5%) between controlled drop zones. In comparison, however, to the ancient inter-valley canals of Peru, which had an average slope percentage of 0.04% (Farrington and Park, 1978), the *bisses* are inefficient. Whilst drop zones help to maintain an adequate hydraulic head, there is no evidence for this being a specific design feature, unlike many Andean systems (Ortloff, 1988; Hastorf, 1989).

Bisse technology developed most thoroughly on the northern Rhône slopes because of the nature of the terrain traversed. Wooden support and suspension systems and rock-cut channels and tunnels were developed to overcome these obstacles. Similar indigenous responses to physical obstacles are seen in Bhutan and Madeira (Smout *et al.*, 1992; Spence, 1994). Isolated design faults have led to inefficiency in the system and very occasionally abandonment (Crook, 1997). There is, however, no evidence for universal design faults, such as the superfluous building of sediment traps on the Levada of the Cape Verde Islands (Haagsma, 1995).

Regular disruption to *bisse* systems is evident on both a minor and major scale. In some locations *bisse* channels were not fixed but able to be moved to adapt to dynamic slope processes. Flexibility was evident in a number of locations where the channel was removed during the winter period to prevent damage from avalanche. This again emphasizes the need for ephemeral structures where the risk of disruption or damage is high. Other risk reduction strategies included covering, burying, and tunneling channels. The ephemeral nature of some *bisse* control structures/technology is mirrored by similar risk strategies in other irrigation systems (Helms, 1981; York, 1992; Adams *et al.*, 1994, 1997; Vincent, 1995). As the security of water supplies improves, so irrigation structures become more permanent. Modernization of these structures has included integrating new more robust materials as they became available. In all cases, the design and materials used in construction were matched to the physical conditions so that they were easy to replicate and replace after periodic disruption. Local resources were used to supply materials and labor, which is a characteristic of many successful irrigation systems, for example the Balinese Subak (Geertz, 1972) and slope off-take systems in Cusichaca (Bowen, 1995) and in Marakwet, Kenya (Adams *et al.*, 1997). Traditional materials and technologies are often more suited to the unpredictable slope conditions found in many mountain environments. For example, since 1977 the reconstruction of canals in Cusichaca, Peru relied on the use of locally available materials—clay, sand, stones, and cactus—instead of cement, as these materials were less liable to destruction by frequent earth tremors (Bowen, 1986).

Nonetheless, new lining or channel materials have been introduced as they became available. These are favored over old materials because they are less porous, which reduces water losses, and longer lasting. In particular, many earthen-cut *bisse* have been lined with concrete, and artificial channels made from galvanized metal and concrete have been increasingly used along conveyance systems. Similar tendencies to modernize with new materials have been observed in most irrigation systems, for example the Levada system of Santo Antao (Haagsma, 1995) and slope off-take systems in Kenya and Tanzania (Adams *et al.*, 1994). Recently, new lighter metals and plastics have been introduced to the *bisses.* This is a recent trend mirrored in the use of PVC pipes in the Levada systems of Santo Antao (Haagsma, 1995) and Chilean irrigation systems (Gwynne and Meneses, 1994). Changes to channel materials have been mirrored in the distribution system. Traditionally made wood or stone divisive and distribution structures are now more commonly made from galvanized metal and aluminum. Since the 1980s, this trend has been reversed by Cantonal and Federal subsidies to redevelop or maintain *bisses* using traditional materials and open channels.

In contrast to other diversion irrigation systems (Vincent, 1995) difficult and expensive maintenance did not lead to rapid abandonment, rather it produced tenacity, strength, and ingenuity to overcome these problems. The construction of technically difficult sections required a high level of transfer of skills from different communes and regions. The highly dynamic nature of the environment has led to costly maintenance both in terms of materials and lives. Depending on the location, *bisse* conveyance maintenance has proved more important than headwork maintenance, as is normal in slope off-take systems (Vincent, 1995). Headwork maintenance can be important in isolated cases, particularly in turbulent spate conditions correlating with seasonal high flow. This is particularly true in slope off-take systems for Sonjo irrigation in Tanzania (Adams *et al.*, 1994). The general rule that the maintenance of meltwater diversion systems is usually easier than highly variable river flows (Vincent, 1995) is not strictly true in the *bisse* context. Conveyance across rugged, steep, or unstable slopes, often with large elevation differences between source(s) and irrigated areas, created a high ratio of canal length to irrigated area in some communes. This has been one motivation for shortening routes and modernizing channels. Modernization and rationalization also has been prevalent in those systems where water supplies are least assured, which generally corresponds to areas where glacial meltwater supplies are not available.

Thus, *bisse* technology has evolved through periods of stasis and change. Many contemporary *bisses* show evidence of older channels and variations on routes. The emphasis has always been on securing, and where possible, upgrading water supplies. Modernization and rationalization of the *bisses* have led to increased channel capacities, the covering of once open channels, the reduction of water losses, and the shortening of conveyance lengths, usually through tunneling projects. In some places this reduces the beneficial impact of water warming in open channels.

Traditional distribution methods, such as damming, cutting, and plugging, are similar to those found in the Levada of Madeira (York, 1992) and Santo Antao

(Haagsma, 1995) and irrigation systems on Gozo (Jones and Hunt, 1994). The severity of the slope and the topography of a field will all influence the efficiency of the distribution. The uniformity of traditional distribution can be poor, even when distribution is aided by irrigators using *délabres* or hose pipes. This contrasts with the constant application depths reported by Haagsma (1995) during distribution from Levada in Santo Antao. Water losses from overland flow and rapid drainage can be large, a problem which is also found in fields irrigated by the Levada of Santo Antao (Haagsma, 1995). In both cases, this is a result of shallow stony soils and steep slopes. In some communes (e.g. Ausserberg, Mund) drainage channels redirect water into lower *suonen*. Soil erosion can result from high velocity flow down steep slopes. This is a particular problem in many Sonjo irrigation systems in Tanzania (Adams *et al.*, 1994). Gravity flow, however, is used primarily on meadow land or orchard crops, which are resilient to these physical conditions and this makes the system fairly robust.

The interval between irrigations (about 1–4 weeks for meadows), whilst not technically efficient in terms of the soil water potential of fields (Crook, 1997), are much shorter and less erratic than the 6 month interval found in the Levada system of Santo Antao (Haagsma, 1995). There is no evidence to suggest that irrigation intervals result in major detrimental growth patterns (i.e. at a level which influences and alters household decision making) to hay crops in the Valais. The modern infrastructure in many communes makes traditional irrigation less labor-intensive, whilst most spray irrigation is automated. This allows Valaisan farmers to pursue more than one income generating activity. Thus, labor availability is a key factor in farm decision making, as seen in the Levada system of Cape Verde (Haagsma, 1995), Marakwet systems in Kenya (Adams *et al.*, 1997), Chilean irrigation systems (Gwynne and Meneses, 1994), and in irrigation systems in Bhutan (Smout *et al.*, 1992).

Structural changes in the wider agricultural economy have driven changes in the *bisse* system similar to experiences in Kenya and Tanzania (Adams *et al.*, 1994; Adams *et al.*, 1997). Spray irrigation has been introduced to irrigate speculative crops with large financial returns. Because of topographical constraints the costs of installing a *réseau d'irrigation* often restricts their distribution to core areas of mountain communes. In some communes, such as Ausserberg and Mund, hybrid distribution systems can be found that blend *ruissellement* from *bisses*, mobile spray irrigation, and *réseau d'irrigation*. The relative importance of each distribution system varies according to altitude, topography, and crop type.

The introduction of spray irrigation and the construction of *réseau d'irrigation* has resulted in a decline in the use of *ruissellement*. This decline is most clearly observed in the Bas and Central Valais. The Haut Valais remains more conservative in its approaches to agriculture than the Valais Romand, which has resulted in greater retention of extensive farming methods, including *ruissellement*, and a reluctance to consolidate and redistribute land holdings. Thus, there is a cultural distinction as well as economic rationale behind the distribution of spray irrigation as is also seen in the irrigation systems of Java (Duewel, 1983). The large scale introduction of spray irrigation into the Haut Valais Ausserberg and Mund communes, however, has occurred within the last five years.

Gravity irrigation has been widely criticized for a number of reasons (Michelet, 1995):

- uneven and infrequent distribution;
- water evaporates and drains rapidly;
- soil erosion is a problem on steep slopes with little or no vegetation cover;
- combined with the effects of the sun and wind it leads to compaction and crusting;
- the method can be impractical because of the slope; and
- low water levels affect efficiency.

There is a tendency, however, to ignore attendant criticisms about spray irrigation, including the fact that its distribution is restricted by topography and cost, spray is susceptible to wind blown evaporation and misdirection, and machinery is prone to mechanical failure and poor management. Thus, in general spray irrigation represents an economy of water use but not necessarily an improvement in total on- farm economic efficiency (Meurer and Müller, 1987). Similar concerns about introducing drip irrigation to parts of England have recently been raised (Weatherhead, 1998). Crook (1997) showed that at a field site in Chermignon, intervals (1–4 weeks) between traditional irrigations and mobile spray irrigation differed little. Soil dried at a similar rate under both systems, so that crops experienced similar levels of stress.

Limited environmental degradation (solonization) resulting from poor management of spray irrigation has occurred in the Valais. This is a recent phenomenon centered around isolated pockets on the Rhône valley floor. In contrast, adequate leaching factors are a product of traditional *meunière* irrigation and sediments accreted during this process have improved the structure of the growing medium.

The spray irrigation of gardens, particularly on newly developed *mayens*, is beginning to be recognized as a problem. There is increasing evidence for a reliance for garden irrigation on limited drinking water supplies, which are separate from normal *bisse* water supplies and are not connected to *réseau d'irrigation*. This practice is illegal in many communes, but is extremely difficult and costly to police and to some extent is tolerated by communes, much in the same way that some illegal activities are tolerated in Marakwet irrigation systems in Kenya (Adams *et al.*, 1997).

The total irrigation efficiency of *bisse* conveyance systems is similar to that found in the Levada of Santo Antao (50%), although the *bisses* do not suffer from the problem of water shortages, as is the case in the Cape Verde Islands (Haagsma, 1995). The extent of the leakage from the *bisse* system makes it appear inefficient, but this overlooks the external benefits of infiltration, leakage, and drainage losses resulting from traditional channels and distribution techniques. The water is not lost; rather it is transferred to other parts of the system. Infiltration and minor leakage can promote vegetative growth next to a *bisse*, which promotes channel and slope stability and benefits woodland and bordering fields. As in the Levada system of the Cape Verde Islands, small scale leakage is tolerated by farmers as long as the main function of the *bisse* is not disrupted (Haagsma, 1995). Likewise, small leaks in the Marakwet system are tolerated because they allow an acceptable level of informal use of this water (Adams *et al.*, 1997). It is proposed that minor water losses during conveyance are a feature of most irrigation systems. The failure to review water efficiency in terms of the whole catchment rather than individual systems is a criticism aimed at state intervention in irrigation in Cape Verde, which started in the 1940s (Haagsma, 1995). The World Bank, whilst planning for drought, has estimated that total water-use efficiency through the repeated reuse of irrigation return flows by lower basin users, both in developed and developing countries, was 87% (Frederiksen, 1992). It is likely that generally lower total catchment efficiencies would be discovered in the Valais because of the abundance of water. Unfortunately, an exact measure of catchment area is difficult because of the complex relationship between water sources and water rights. It is evident, however, that the integrated nature of irrigation catchments in mountain zones requires that intervention and changes to individual systems should not be carried out until the full consequences to lower systems are ascertained.

CONCLUSION

With each renovation or modernization, *bisse* constructors have sought to improve channel efficiency and security. Thus, the *bisses* possess a dynamic which is adaptive to periods of technical continuity and change. The *bisse* system, whilst originally incorporating low technology but at times ingenious solutions to water shortage, has not failed to adapt to new technical and economic opportunities when appropriate.

Modernization and rationalization in the system have followed the principle of securing and improving water supplies so that agriculture remains economically competitive at the level of the household. The 20th century has witnessed a major modernization and rationalization of Valaisan agriculture and of the whole Valaisan economy; this has had implications for *bisse* irrigation. Principally, it has resulted in a focus on intensively cultivated crops in favorable areas (close to the market, with an environmental advantage resulting from climate), such as the Rhône plain and slopes. The security of water supplies in these areas became paramount, which meant that technological changes to *bisses* have been most marked in these areas. This has required changes to the infrastructure, such as the consolidation of landholdings, construction of *réseau d'irrigation* to allow systematic spray irrigation, and changes in the pattern of agricultural employment which allow more personal freedom and provides water economies. This allows people to find dual incomes and farm on a part-time basis.

The rationalization of agriculture has led to its decline in the mountain zone (i.e. all areas outside the Rhône valley and valley slopes). Mountain agriculture remains, but it is reliant on government subsidies for survival. In these locations, there is more incentive to maintain the agricultural landscape for tourism rather than for any economic incentives resulting from agricultural production. This has led to partial and total abandonment of many *bisses*, particularly on the *mayen* and alps where housing and hotel development is often extensive. Many moribund *bisses* in these zones have tourist potential, which can be enhanced by redevelopment with traditional materials and techniques (Crook and Jones, 1999).

The priority of those operating the surviving *bisses* is to maintain and improve water efficiency by reducing losses in conveyance and distribution systems. This has meant a switch from traditional to modern materials and the increased use of enclosed or underground *bisse* channels. A large number of *bisses* are integrated into HEP projects which has increased the number of tunnels. Like *bisse* conveyance systems, *réseau d'irrigation* have also been expanded over time. Coarse and abrasive sediments carried in glacial meltwaters have prevented the widespread introduction of drip and subterranean irrigation to the Rhône plain, as have the costs of installation and operation. Similar restrictions on development have been observed in Santo Antao (Haagsma, 1995).

The sustainability of *bisses* will only be assured by their remaining responsive to the individual needs of the household. Changes in the *bisse* system have not been wholesale, rather they only occur where economically sustainable livelihoods at the level of the household are maintained. Through the actions of *consortages* and communes, technical innovations have been incorporated into design principles when economically significant. The wider role of irrigation, however, should not be overlooked. Traditional thoughts about using irrigation solely to intensify agriculture and improve agricultural outputs in mountain locations are inappropriate. Extensive irrigation practices help to maintain traditional rural landscapes which are crucial to the summer tourist industry; they also promote slope stability and reduce the fire risk on slopes. The true costs of the benefits must be understood by governments to prevent the destruction of these systems. There is evidence to suggest that these factors have been recognized in the Valais with large public and private sector investment in abandoned, moribund, and operational *bisses*. Thus, integrated multi-functional irrigation systems seem to provide the best opportunity for maintaining sustainable livelihoods in the Valais. These multi-functional objectives may also be appropriate in other mountain environments which are well integrated into developing lowland economies.

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