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A hydrological analysis of terrestrial and Martian gullies: Implications for liquid water on Mars

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ABSTRACT

Understanding the role and amounts of liquid water involved in Martian gully formation is critical in studies of the Martian hydrosphere and climate. We performed hydrological analyses using the Manning and Darcy–Weisbach equations in order to infer flow velocities and discharge rates from channels at two gully sites in Noachis Terra, Mars. The results of these analyses were compared with analogous hillside gullies in Australia. We found the velocities and discharge rates for the terrestrial gullies to be comparable to velocities and discharge rates of some small Martian gully channels. In contrast, velocity and discharge in some larger Martian gullies were almost an order of magnitude higher, equating with catastrophic flows on Earth. We postulate that the larger gully channels were more likely formed by a number of smaller flows in a similar manner observed in some terrestrial gullies, a scenario that does not require vast amounts of liquid water to be stable under Martian conditions. In addition, we found that post-fluvial channel widening may have acted on the Martian gullies, probably by dry mass wasting, leading to larger channels than were originally carved by liquid water. Future hydrological analyses of Martian gullies will lead to a greater understanding of the relative importance of dry mass wasting compared to liquid water erosion.

1. Introduction

Martian gullies resembling water-carved hillside gullies on Earth were discovered by Malin and Edgett (2000). These small-scale features typically consist of an alcove, V-shaped channel, and a depositional apron and predominate in the middle to high latitudes of Mars (Malin and Edgett, 2000; Milliken et al., 2003). Martian gullies have attracted much attention as their modification of youthful features such as polygonal terrain and dunes indicates their extremely young age, which has implications for the existence of liquid water on Mars within the past 1.5 My (Heldmann et al., 2007). Many models of Martian gully formation have been proposed, including initial nonfluvial models such as dry mass wasting (Treiman, 2003), liquid CO_2 (Hoffman, 2001; Musselwhite et al., 2001), and frosted granular flows (Hugenholtz, 2008). Other landforms sharing some of the features of gullies such as alcoves and depositional regions have been observed on the Moon (Bart, 2007; Senthil Kumar et al., 2013) and even Mars (Dickson and Head, 2009), but they consistently lack terrestrial stream-like features, such as sinuous V-shaped channels, digitate depositional slopes lower than the angles of repose of dry material, and concave up profiles attributed to fluvial-based systems (Heldmann et al., 2007; Dickson and Head, 2009; Mangold et al., 2010; Hernandez et al., 2014). Analyses of slopes have been an important process in inferring types of gully erosion and have centred around angles of kinetic friction with values < 21° suggesting fluid-based activity (Kolb et al., 2010), angles of repose for Martian regolith (26–32°; Pouliquen, 1999), and dry mass wasting (>35°; Conway et al., 2011) to infer fluidised or nonfluidised activity. Although angles of cohesive materials, such as rocks or bonded clays, are also affected by their shear strength (Selby, 2000; Osadebe et al., 2014), the level of cohesiveness of Martian regolith has only been analysed at an extremely limited number of landing sites, revealing a consistence similar to moderately dense soils on Earth, none of which have included gullies (Barlow, 2008). Thus, previous gully research has primarily been restricted to assuming regoliths in which gullies form behave as dry or loosely consolidated material (Pouliquen, 1999; Kolb et al., 2010; Lanza et al., 2010; Conway et al., 2011). Water-based models for gully formation are preferred by recent researchers (Dickson and Head, 2009; Araki, 2012) and include: water sourced from aquifers (Malin and Edgett, 2000; Heldmann and Mellon, 2004), melting of snow (Christensen, 2003), or degradation of ice-rich, latitude-dependent mantle (LDM; Schon and Head, 2011, 2012). The LDM is a unit appearing smooth in images, partially responsible for early observations of terrain softening (Squyres and Carr, 1986) and draping much of the Martian surface at mid to high latitudes. It is thought to represent ice-rich material atmospherically deposited during

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periods of high obliquity (Kreslavsky and Head, 2002; Dickson and Head, 2009; Schon and Head, 2011; Dickson et al., 2014).

The consensus of most researchers at present favours a top-down snowmelt model for gully erosion, given the observations of gullies located on isolated peaks or elevations not consistent with an aquifer layer (Dickson and Head, 2009; Levy et al., 2011) and given the failure of ground penetrating radar studies to identify any aquifer reservoirs at gullies previously thought to have formed by aquifers (Nunes et al., 2010).

The amount of liquid water required to form gullies on Mars remains controversial as there has been no direct method of confirming the presence of water or inferring the amount and discharge rates involved in gully erosion. Estimations of flow velocities and discharge rates will provide an insight to the amount of liquid water required to form Martian gullies and whether this concurs with calculations of similar activity observed terrestrially. Popular formulae for inferring fluid velocity and discharge rates in terrestrial and Martian systems are the Manning and Darcy–Weisbach equations (Manning, 1891; Selby, 1982; Wilson et al., 2004; Kleinhans, 2005; Jouannic et al., 2012; Parsons et al., 2013; Levy, 2014). We describe these equations in detail in Section 2 and note that they have been extremely popular in velocity and discharge calculations in terrestrial gully and debris flow systems (e.g., Mizuyama et al., 1988; Rickenmann and Zimmermann, 1993; Garcia-Castellanos and Villasenor, 2011) and in fluvial channels on Mars and Titan (Wilson et al., 2004; Kleinhans, 2005; Jaumann et al., 2008; Parsons et al., 2013), and are being increasingly used to investigate Martian gullies (Hart et al., 2010; Jouannic et al., 2012; Narlesky and Gulick, 2014). In this work we aim to trial the use of Manning and Darcy–Weisbach equations to estimate flow velocities and discharge rates at two gullied sites in Noachis Terra, Mars, and compare these calculations with results from previous analyses of velocity and discharge at other Martian gullies (Hart et al., 2010; Parsons and Nimmo, 2010; Jouannic et al., 2012; Levy, 2014; Narlesky and Gulick, 2014). We also compare our Martian-derived velocity and discharge estimates results with those obtained at a semiarid gullied site at Island Lagoon and at a temperate gullied site at Lake George, Australia. We use this comparison between Martian and terrestrial gullies to determine the utility of these equations to estimating fluid discharges in gullies on Mars.

1.1. Terrestrial analogues

Analysis of terrestrial analogues, that is earth-based landforms that share similar characteristics as features found on other planets such as Mars, allows for the use of direct measurements and fieldwork to characterise processes and evolution of the Martian surface where direct measurements are extremely limited (Sharp, 1980; Chapman, 2007). Examples of such fieldwork include the study of gullies in periglacial environments, such as Svalbard (Reiss et al., 2011), Iceland (Hartmann et al., 2003), and the Antarctic Dry Valleys (Dickson and Head, 2009; Levy et al., 2009). This previous research was conducted in order to characterise gullying activity in terrestrial cold environments and its application to the investigation of similar activity occurring in the freezing climate of Mars. Analogue studies of terrestrial gullies have also been conducted in semiarid environments, such as Meteor Crater, Arizona (Kumar et al., 2010), and mudflows in the Chilean Atacama Desert (Heldmann et al., 2010). We note that significant differences exist between the climate and geology of Earth and Mars and that the most extreme terrestrial environments, such as the arid Atacama Desert or Antarctic Dry Valleys, are much warmer and wetter than the hyperarid, low pressure, and freezing climate of Martian gully sites (Barlow, 2008; Dickson and Head, 2009). In addition, equifinality, where differing processes create similar morphology such as terrestrial gullies formed by rainfall-fed aquifers (Soms, 2006) or snowmelt in periglacial environments (Lee et al., 2001), requires analogue researchers to carefully consider and understand the local environment of a study site, including differences in climate and geology. Nevertheless, the study of terrestrial analogues has been a cornerstone for inferring geomorphic processes in planetary science (Hartmann, 1974; Komar, 1979; Sharp, 1980; West et al., 2010).

Fig. 1A–C shows the regional locations for the gully sites analysed in this work including (A) Noachis Terra, (B) Lake George and (C) Island Lagoon. A summary of our analyses of the Lake George and Island Lagoon gullies (Hobbs et al., 2013, 2014) is presented below.

1.2. Studied terrestrial gullies

Our terrestrial analogues at Lake George (Fig. 2A) exist within a temperate climate on the western escarpment of the Lake George fault (De Dekker, 1982). Annual rainfall of the area is ~650 mm. The gullies have been shaped primarily by superficial water runoff, probably initiated during a colder and drier glacial period (Singh et al., 1981; Singh and Geissler, 1985) and reactivated following land clearing by European settlement (Coventry, 1976). The channels of these gullies were found entrenched within loosely consolidated material with sizes decreasing from tens of centimetres at the gully alcove to millimetre size alluvium at the depositional fan. The channels had also eroded to bedrock, forming benches and dry waterfalls along their length. Gullies A and D (Fig. 2B) were the largest of the gullies studied at the site and consisted of dual alcoves and V-shaped channels that had incised their respective depositional fans. We compared the gullies at Lake George with gullies and dry ravines located within a crater at Noachis Terra, Mars, hereafter identified as Reiss Crater. We originally chose the gullies at Lake George as they were unambiguously formed by the action of liquid water and shared many of the morphological characteristics of gullies we studied in Reiss Crater, such as alcoves, V-shaped channels and depositional aprons. Establishing a baseline for the action of liquid water in forming terrestrial gullies led us to infer the role that liquid water and local conditions played in the formation of gullies on Mars. We found that despite significant climatic differences between the two study regions, the morphology of both sites was strongly controlled by the thickness of erodible material and the presence of bedrock. Previous research into structural control and geology of Martian gullies (Gilmore and Phillips, 2002; Treiman, 2003; Kumar et al., 2010) has suggested that this is an important consideration in Martian gully morphology. Our studies at Lake George, and also Island Lagoon, near Woomera, South Australia, allowed us to assess the influence of local geology on Martian gullies. We also observed evidence of multiple erosion events acting on the Lake George gullies, with smaller channels embedded within larger ones and channels incising depositional fans. This suggests that gullies at this site may have been formed through multiple events and have enlarged to their present size through a series of smaller gullying processes. The cumulative action of a number of processes to form larger features is consistent with findings of previous research on Martian gullies (Dickson and Head, 2009; Levy et al., 2009; Schon and Head, 2012; Dickson et al., 2014) and suggests that this is a relevant mechanism in the formation of Martian gully morphology. The long profiles of the Lake George gullies were significantly affected by the presence of bedrock and had also inherited the palaeoshore abrasion observed in the host escarpment. Thus, although concave up long profiles have previously been identified with fluvial activity (Smith et al., 2000; Goldrick and Bishop, 2007; Larue, 2008) local conditions and geology must be taken into account before any meaningful inferences on proposed mechanisms can be made.

The semiarid Island Lagoon site in South Australia (Fig. 3A) has previously been investigated as a Mars Society mission staging area, chosen because of its analogous geomorphology to Mars (Mann et al., 2004). Island Lagoon receives an average of 200 mm of sporadic rainfall per year (Grove et al., 1977; Williams et al., 1998). The gullies (gully E, Fig. 3B and gully G, Fig. 3C) were located on the northern escarpment embedded within a rocky matrix with sparse vegetation. The gullies residing within the escarpment were composed of thinly bedded and flaggy-

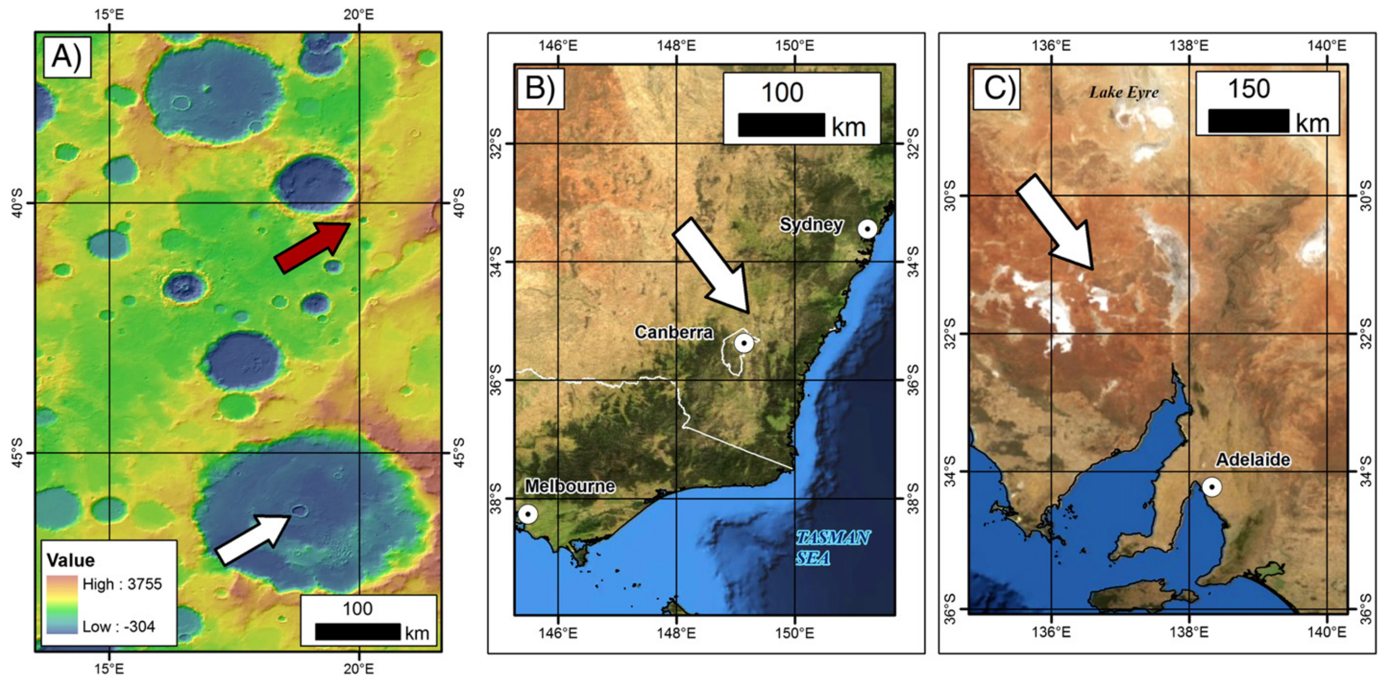

Fig. 1. (A) Overview of gully sites in Noachis Terra, Mars. Top (red) arrow marks location of Reiss Crater (the primary gully site studied in Hobbs et al., 2013). Bottom (white) arrow marks location of gullies in Kaiser Crater. Elevation values in metres. (B) Location of gullies at Lake George, New South Wales. (C) Location of gullies at Island Lagoon, South Australia.

weathering sandstones, siltstones, and mudstones of the Corraberra Sandstone Member (Johns et al., 1981). This site was chosen for its paucity of vegetation and extremely limited amount of water available for gully erosion, in contrast to the temperate climate of Lake George. We also wished to analyse how the strong structural control of the Island Lagoon escarpment affected formation and erosion of the gullies at the site. The Island Lagoon gullies revealed structural control afforded by erosion resistant rock layers, and more erodible colluvium underneath likely caused catchment-fed alcove and subsequent channel erosion through undercutting of boulders and localised rockfalls. In addition, the local geology concentrated fluvial flow to form V-shaped channels that terminated in fluidized debris aprons. The flows along the main gullies were fluid-rich, and debris flow activity appeared to be confined to smaller features located on the walls bounding some of the main gully sites. This suggested that, although Island Lagoon is a semiarid site, water was the primary erosive agent and sufficient quantities were available to create fluid-rich erosion with lower sediment concentrations than would be expected of debris flows. The presence of superimposed channels and incised depositional fans suggested that periodic rainfall had created a history of a number of erosion events of differing intensity at the site. As with Lake George, the long profiles of the Island Lagoon gullies were heavily influenced by multiple exposures of bedrock, though presented a concave up profile suggested by previous research to indicate fluvial erosion (Smith et al., 2000; Goldrick and Bishop, 2007; Larue, 2008).

In addition to Island Lagoon and Lake George, we investigated gullies in the subhumid region of Pasture Hill, New Zealand. High resolution elevation data were not available for this site, and direct field measurements of water flow could not be made, which precluded consideration of this study area for hydrological analysis. Nevertheless, the periglacial conditions in which these gullies were found provided useful analogues for proposed Martian gully processes. This site revealed the important contribution made by frost shattering and surface creep in the processes of gully erosion. Frost shattering provided alluvium that coalesced within alcoves and formed talus flows similar in appearance to the dry ravines at Reiss Crater. Characterisation of these talus flows proved insightful, and we noted that they followed local topography, forming sinuous shapes in the upper slopes in a similar manner to dry flows modelled by Mangold et al. (2010). None of the talus flows possessed V-shaped channels and all displayed low concavities, similar to the dry ravines located at Reiss Crater.

We also observed an increased complexity in gully morphology as compared to the other two studied terrestrial sites, such as infilled alcoves similar to those observed in Kaiser Crater gullies, and depositional and water erosion regimes located within the alcove of one of the gullies. We thus inferred that the Pasture Hill gullies exhibited a complex regime of erosion and deposition, and although high slopes were favourable for dry mass wasting processes, which we did observe in these regions, they do not necessarily exclude the possibility of fluvial processes playing a role in these areas. We also found that gully slopes were consistently inherited from the host crater wall or escarpment and formed on a wide variety of slopes. This was readily apparent in the much shallower slopes of the eastern Pasture Hill site compared with those of the western slope gullies.

In summary our study of terrestrial gullies showed the following:

- terrestrial analogues can provide a useful benchmark to compare Martian gullies against;
- gully formation is not necessarily restricted to a single process;
- slope inheritance, thickness of erodible material, and presence of bedrock have greatly influenced gully slope and morphology; and
- interpretation of gully forms should be placed in context of local environments.

1.3. Studied Martian gullies

Fig. 4A–C shows details of the gullies selected from Reiss Crater for hydrological analysis. Despite being located within the same crater rim these features displayed diverse morphologies ranging from the alcove-less, single channel gully 1 (Fig. 4A), dual alcove gully 2 (Fig. 4B), and broad-channelled gully 3 (Fig. 4C). Gully 3 was the largest gully, possessing the highest channel volume:length ratio of 810, while gully 1, the smallest, had a ratio of 72 (Hobbs et al., 2013). In addition, smaller channels were superposed within the larger channels of gullies

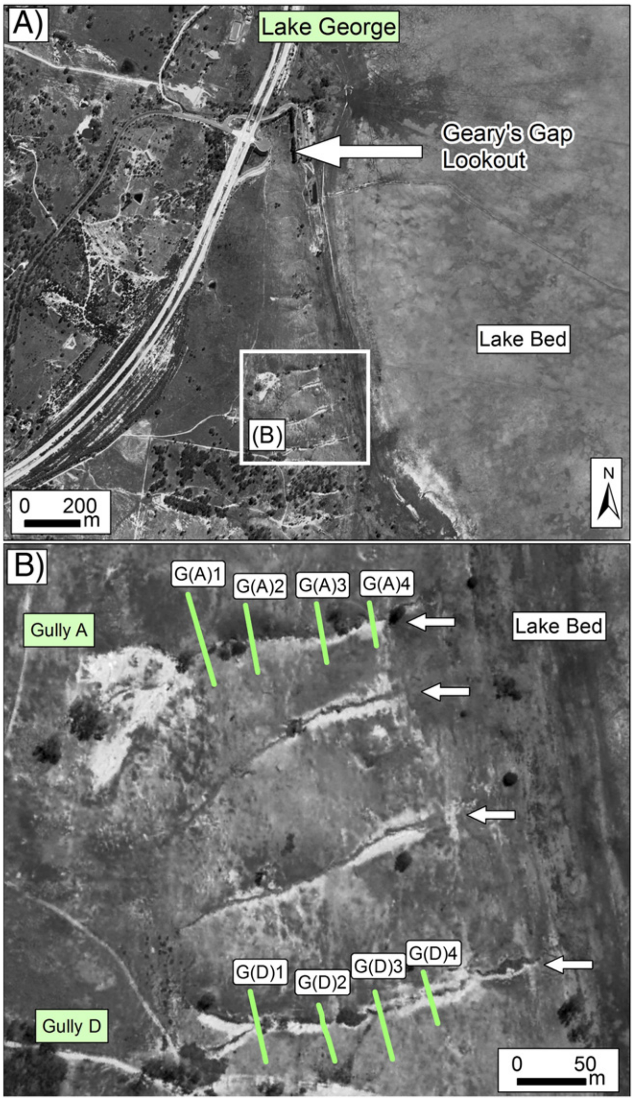

Fig. 2. (A) Overview of Lake George gullies in the vicinity of Geary's Gap, New South Wales, which were subjected to hydrological analysis. Location of inset B is shown. (B) Detail of gullies A and D. White arrows mark depositional regions of gullies A and D, as well as additional gullies at this site. Apart from labelling terrestrial gullies with letters, the labelling style is similar to those used for the Martian gullies.

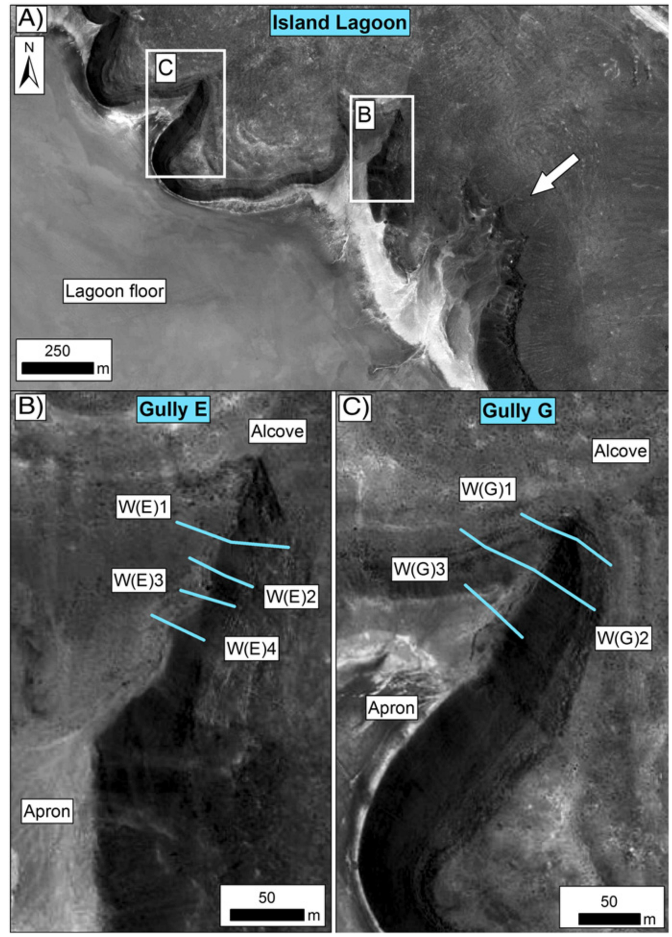

Fig. 3. (A) Overview of gullies located on the northern escarpment of Island Lagoon, which were subjected to hydrological analysis. Locations of insets B and C are shown. White arrow marks the location of additional gullies studied in Hobbs et al. (2014). (B) Gully E showing the location of cross profiles used for hydrological analysis. (C) Island Lagoon gully G. Apart from labelling terrestrial gullies with letters, the labelling style for Island Lagoon is similar to those used for the Martian gullies.

2 and 3 (dashed lines, Fig. 4B–C). Our research, based on long profile and thermal inertia analysis, indicated that gullies at Reiss Crater had eroded into fine-grained material, probably LDM, and had probably not yet eroded down to bedrock (Hobbs et al., 2013). Previous research has revealed that Martian gullies are quite commonly embedded within LDM, and it is the degradation of this ice-rich material that has provided the source of water required for gully erosion (Dickson and Head, 2009; Schon and Head, 2011, 2012; Dickson et al., 2014; Levy et al., 2014). Our findings at Reiss Crater are consistent with this proposed water-based mechanism for gully erosion. Additional indications of liquid water erosion at this site included the V-shaped channels and concave up profiles that were exclusively located on the northern rim of Reiss Crater. The gullies were also subjected to multiple erosive events, as indicated by superposed inset channels within the channels of some of the gullies and overlapping of depositional fans. Although we searched for possible morphological evidence of debris flows, none of the depositional fans possessed lobate morphology related to debris flows and only the inset channel of gully 2 showed evidence of a levee (Fig. 8C in Hobbs et al., 2013). Furthermore, we were unable to clearly locate a definitive source for the inset channels of gullies 2 and 3 of Reiss Crater and thus excluded them from catchment area analysis.

In order to compare the morphology and possible influence of water erosion of the gullies on the northern rim, we also analysed features on the southern, equator-facing rim. The equator-facing rim of Reiss Crater is located at latitudes where temperature modelling suggested that accumulation of water-based snow would be unlikely compared to the more favourable northern, polar-based slopes (Morgan et al., 2010). We thus expected features suggestive of water-based erosion, such as concave up profiles and sinuous V-shaped channels, to be absent on the equator-facing rim. In stark contrast to the gullies on the northern rim these features, which we defined as dry ravines, possessed a lack of LDM material and an abundance of bedrock exposures, as inferred in thermal inertia analysis and seen on HiRISE imagery. Similar features have been observed on equator-facing slopes of other craters at this latitude (e.g., Schon and Head, 2012). The alcoves of the dry ravines possessed a spur and gully appearance attributed to dry mass wasting seen elsewhere on Mars (Hartmann et al., 2003; Dickson and Head, 2009) and wide, U-shaped profiles heavily influenced by bedrock exposures. Material appearing fine-grained at the resolution of HiRISE imagery had flowed from the alcoves to form deposits that were longer than those of the northern gullies. As with the Pasture Hill talus flows described in Section 1.2, long profiles of the dry ravines were virtually linear, with no evidence of the concave-up profile attributed to fluvial activity (Smith et al., 2000; Goldrick and Bishop, 2007; Larue, 2008).

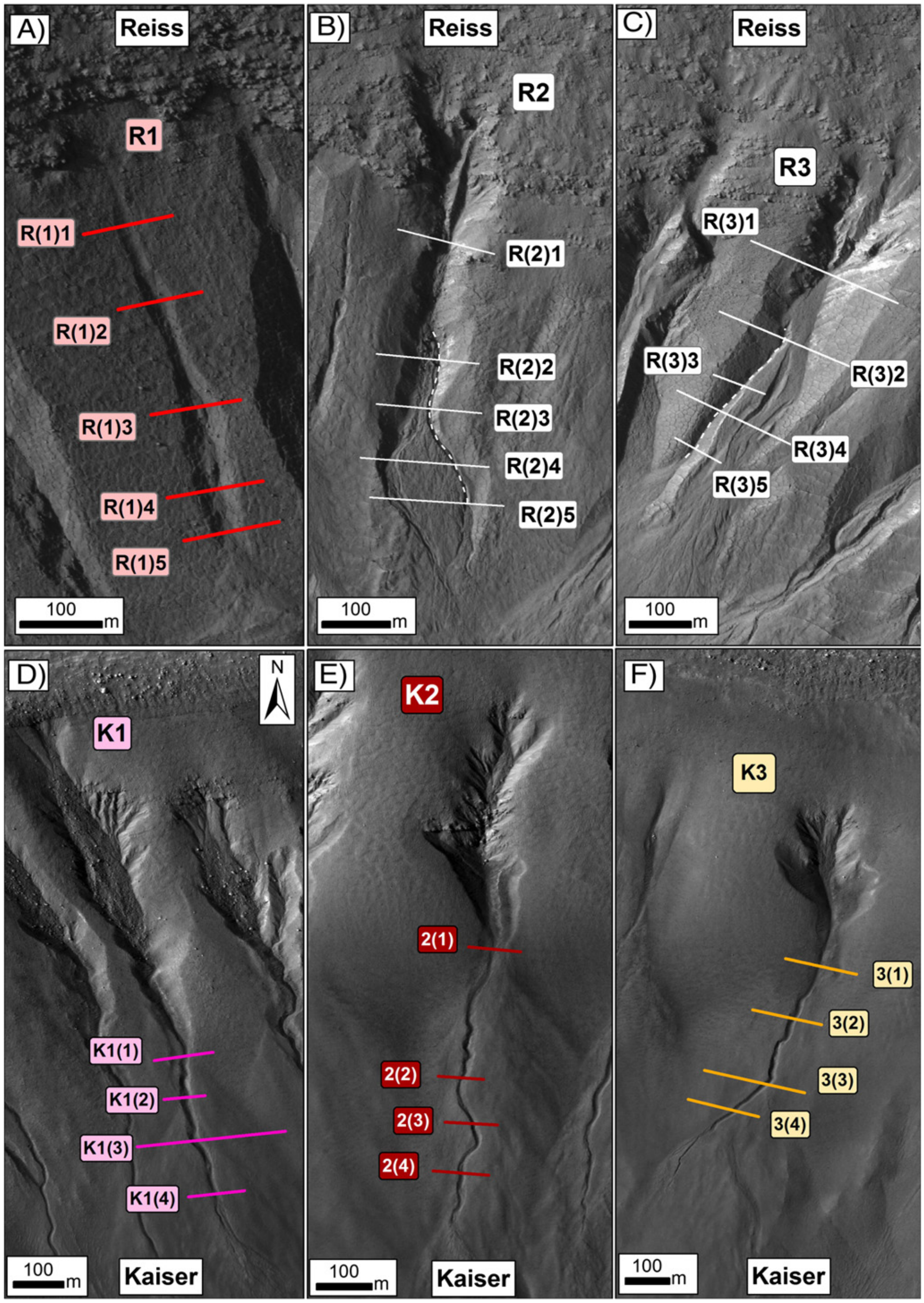

Fig. 4. Overview of Martian gullies studied for hydrological analysis. Sampled channel cross-sectional profiles are labelled with site letter (e.g. R for Reiss Crater), gully number (e.g. 1 for gully 1) and cross profile number for each gully. (A–C) Overview of Martian gullies within the northern rim of Reiss Crater from Hobbs et al. (2013) in Noachis Terra. Inset channels, where present, are shown with dashed line. (D–F) Analysed Kaiser Crater gullies.

Striations and elongated craters located within the dry ravines suggested that although liquid water was probably not eroding the ravines, a limited amount of frost activity was present on the equator-facing rim to drive these erosive processes. The action of this process may resemble that operating on the Pasture Hill talus flows.

The gullies we analysed at the Kaiser Crater site are shown in Fig. 4D–F and show evidence of multiple erosive processes. We chose these gullies as analogues as they appeared morphologically similar to the Pasture Hill gullies and the Island Lagoon debris flows that we studied (Section 1.2). Previous research at this site using apex slope and slope area analyses revealed that the slope and morphology of the gullies were consistent with pore pressure-triggered fluidised flow (Kolb et al., 2010; Lanza et al., 2010; Conway et al., 2011). These gullies were also found embedded within fine grained material, though possessed a different morphology to those at Reiss Crater. The gully alcoves appeared much more pronounced, being much wider than the sinuous channels below them. In contrast to Reiss Crater, these gullies exhibited prominent leveed channels. Although the presence of levees has been cited as evidence for debris flow activity on Earth and Mars (Lanza et al., 2010; Levy et al., 2010; Reiss et al., 2011), levees have also developed in fluvial channels, such as flooding rivers (Adams et al., 2004; Rowland et al., 2009), alluvial deep water fans (Normark et al., 2002), and tidal channels (Van der Wegen et al., 2012). In addition, terrestrial debris flows have been observed without levees (Selby, 2000). Thus, the presence of leveed channels may not necessarily indicate debris flow activity and it is possible that the leveed channels at the Kaiser Crater site may not indicate the presence of debris flows. Evidence for subsequent erosion was also present within some of the gully channels, though it was much less distinct than for Reiss Crater. As with Reiss Crater our analysis of the Kaiser Crater gullies revealed sinuous, V-shaped channels incising into depositional fans, possessing slopes below the angle of repose, and concave up profiles that suggested the dominant erosive agent was liquid water. We also found that these gullies may have evolved through a complex interaction of a number of fluvial and nonfluvial processes. Localised accumulations within topographic lows of the gully alcoves may be of frost-shattered talus sourced from high (>35°) slope regions in the upper alcoves, where spur and gully morphologies were also observed. This material has probably deposited through a combination of creep and fall in a similar manner to what we observed occurring in some of the gullies at Pasture Hill, New Zealand. Locations of this overlying material may also have concentrated subsurface water to facilitate channel erosion.

In summary our study of Martian gullies showed the following:

- pole-facing gullies at both sites exhibited morphology most likely to have been formed by liquid water;
- liquid water may be sourced from degradation of LDM or other ice-rich material accumulated within topographic hollows of crater walls;
- the gully channels had yet to erode to bedrock and exhibited smooth, concave up profiles;
- as with Earth, Martian gully formation is not necessarily restricted to a single process; and
- localised geology and environment have a significant impact on Martian gully morphology.

2. Hydrology

Fluids, including water, move downhill at a velocity dependent on a variety of factors including slope, the viscosity of the fluid, roughness of the surface, and the force of gravity acting upon them (Leopold et al., 1964; Selby, 1982, 1991). The resultant velocity can then be used to calculate flow discharge and to infer the amounts of water involved. On Mars, direct measurements of water velocities, sediment concentrations, and discharge rates are impossible, requiring these to be modelled through flow equations. Many different modelling approaches and equations have been used in terrestrial fluvial channel systems (e.g., Istanbulluoglu et al., 2003; Sidorchuk et al., 2003), with one of the most popular being the Manning equation (Manning, 1891; Selby, 1982):

$$v = (1/n)\mathrm{R}^{2/3}\mathrm{S}^{1/2} \tag{1}$$

where v is the average velocity of the flow in m s^{-1}, S is the tangent of the water surface slope, n is the Manning coefficient, and R is the hydraulic radius. Hydraulic radius R represents the ratio between channel cross-sectional area of the wetted channel (A) and the portion of the channel in contact with water, being the 'wetted perimeter' (P_w) in the following relationship:

$$R = A/P_w. \tag{2}$$

The Manning coefficient n has been termed a roughness parameter (Selby, 1991) and is dependent on the coarseness of the surface material. Smoother surfaces with smaller grain size possess lower Manning coefficients than coarser material, and typical n values for natural streams range from 0.025 for clean, smooth channelled streams to 0.75 for rocky bedded streams with standing timber. An increase in n equates to a greater resistance to flow and hence reduced flow velocity.

A number of researchers have postulated limitations on Manning's equation for applications to Mars, such as the difficulties in estimating channel depth from orbital imagery (Carr, 1979). Nevertheless, Komar (1979) adapted Manning's equation to account for the gravity difference between Mars and Earth:

$$v = (1/n)(g_m/g_e)^{1/2}R^{2/3}\,S^{1/2} \tag{3}$$

where g_m is the gravity of Mars (3.72 m s^{-2}) and g_e is the gravity of Earth (9.81 m s^{-2}).

Uncertainties in correlating terrestrially derived roughness coefficients for application to Martian environments also exist (Burr et al., 2002; Wilson et al., 2004). Additional limitations include the difficulty in constraining channel parameters, such as inferring the actual water level flowing within the channel for Mars, which would then adversely underestimate or overestimate velocity and hence discharge flows (Carr, 1979; Kleinhans, 2005). This has lead several researchers (Wilson et al., 2004; Kleinhans, 2005; Parsons et al., 2013) to utilise the Darcy–Weisbach friction equation in which gravity is explicitly expressed:

$$v = ((8gRS)/f)^{-1} \tag{4}$$

where g equates to gravity, f is a dimensionless friction factor, and other variables are as previously defined. A relationship for f that has been used for Martian applications (Kleinhans, 2005; Parsons et al., 2013) is given as:

$$(8/f)^{-2} = 5.74\log_{10}(12.2(\mathrm{R}/2.5D_{50})) \tag{5}$$

where D_{50} is the median grain size of the channel bed sediment distribution (i.e., 50% of grains are smaller than D_{50}) and R is the hydraulic radius. This equation is also useful over a wide range of roughness coefficients and has been tested in a comparison with a data set of 190 terrestrial rivers that included straight and meandering forms with sand and gravel beds (Kleinhans, 2005). Roughness predictors were found to be dependent on slope and the relative roughness ratio and were highly variable, though these variations tended to cover ranges inferred for Martian channels (Kleinhans, 2005). The Darcy–Weisbach friction factor has also been derived from Manning's roughness coefficient in previous channel studies (Lang et al., 2004), being related to n by:

$$f = 8\,\mathrm{g}\left(n/\mathrm{R}^{1/6}\right)^2. \tag{6}$$

In addition, Wilson et al. (2009) have suggested the following formula for f in situations of high slopes and multiple plunge pools (solving for f):

$$f = 8/\left(5.75\left\{1-\exp\left[(-0.05\mathrm{d}_s)/\left(D_{90}\mathrm{S}^{1/2}\right)\right]\right\}\times\log_{10}[8.2\mathrm{d}_s/D_{90}]\right)^2 \tag{7}$$

where D_{90} is the channel bed grain size where 90% of grains are smaller than D_{90} and d_s is the total depth of water plus sediment, assuming that the depth of the sediment layer is insignificant compared to the water. Table 1 lists all parameters used in the above hydrology equations for clarity.

Although the Darcy–Weisbach equation has been recommended over the Manning equation for Martian fluid study owing to the explicit expression of g (which is also present in Komar's (1979) adapted Manning equation for Mars) and updated terrestrial benchmarks for f, theoretical limitations are still present. Wilson et al. (2004) modelled flow conditions in Martian channels and compared the effect of differing

Table 1
Definitions of hydrological parameters used in Manning and Darcy–Weisbach calculations.

Parameter	Definition	Units
v	Flow velocity	m s^{-1}
Q	Flow discharge rate	m^3 s^{-1}
t	Flow time	s
S	Tangent of water surface slope	N/A
n	Manning coefficient	$s/m^{0.5}$
A	Cross sectional area of wetted channel	m^2
P_w	Wetted perimeter (portion of channel in contact with fluid)	m
R	Hydraulic radius (ratio between A and P_w: R = A / P_w)	m
g_m	Martian gravity (3.72 m s^{-2})	m s^{-2}
g_e	Terrestrial gravity (9.81 m s^{-2})	m s^{-2}
f	Darcy–Weisbach friction factor	N/A
D_{50}	Median grain size of the channel bed sediment distribution (50% of grains are smaller than D_{50})	m
D_{90}	90% grain size of the channel bed sediment distribution (90% of grains are smaller than D_{90})	m
d_s	Total depth of water plus sediment. Assumes depth of the sediment layer is insignificant compared to depth of water	m

channel bed roughness in relation to the Darcy–Weisbach friction factor on overall fluid velocity. They found that differing channel bed roughness made little difference (22% minimum–maximum) on water flow velocity variation and attributed it to Martian water depths being much larger than the sizes of channel bed roughness. In addition, previous research (Kleinhans, 2005) has relied on the very limited in situ terrain measurements available from Martian landers in the estimation of f. The wealth of remotely sensed data gathered by orbiting spacecraft over the past few decades has revealed the extreme diversity of Martian geology (Barlow, 2008). Although Martian global roughness calculations have been conducted using MOLA (Kreslavsky and Head, 2002) and Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) radar returns (Campbell et al., 2013), these data sets are too coarse to provide meaningful inferences on finer scale features such as gully channel roughness. Estimations of surface roughness of the bulk of the planet are thus limited to inferences from thermal inertia data (Christensen et al., 2004; Putzig and Mellon, 2007) or equivalent terrestrial analogues (Sharp, 1980; Chapman, 2007). Given that terrestrial channel bed compositions show extreme variation (Leopold et al., 1964; Selby, 1991), lander-based data will at best provide a guide and Martian channel bed roughness values will still need to be inferred with a considerable degree of uncertainty (McIntyre et al., 2012). Wilson et al. (2004) suggested an optimal Manning's roughness coefficient of 0.0545, though other values have been used in previous Martian research (e.g., Lucas et al., 2009). Moreover, the development of metre-scale resolution elevation data sets has enabled unprecedented morphometric analysis of small-scale fluvial systems, such as gullies (Lanza et al., 2010; Okubo et al., 2011), mitigating uncertainties in measuring channel depth and slope. The Mars-adapted Manning equation is thus a viable equation for inferring Martian fluid flow and has been used in conjunction with HiRISE DEMs for inferring the fluvial properties of dune gullies (Jouannic et al., 2012) and Martian hillside gullies (Hart et al., 2010; Narlesky and Gulick, 2014). We note that a limitation of applying hydrologic equations to Martian gullies is the estimation of water slope, as opposed to using thalweg slope (Selby, 2000). Such differentiation is not possible on Mars given the total lack of observations of flowing water. Use of thalweg slope may thus overestimate the velocity and hence discharge of water flowing through these features, but regardless of this limitation it remains the most viable approach.

Gully velocities have also been modelled by assuming the erosive agent has behaved as a Bingham fluid, where flows have contained a high sediment concentration (Mangold et al., 2003). Estimations for dune gully velocities ranged from 1 to 7 m s^{-1}, with parameters for the fluidised material to be within the range of terrestrial debris flows. High sediment concentrations occur in debris flows, which have been proposed as a mechanism for Mars gully formation (Conway et al., 2011; Reiss et al., 2011). Debris flow deposits exhibit leveed channels and lobate apron morphology, which have rarely been observed unambiguously at isolated sites on Mars (Conway et al., 2011; Reiss et al., 2011). Although our previous research indicated possible evidence for debris flows occurring within the lower regions at Kaiser Crater gullies (Hobbs et al., 2014), similar evidence for such activity at Reiss Crater was unclear (Hobbs et al., 2013). In addition, debris flow activity was not interpreted to be a major process at terrestrial sites at Lake George or Island Lagoon in Australia (Hobbs et al., 2013, 2014). We considered whether Manning and Darcy–Weisbach equations were appropriate for analysis of Martian gullies and note that Manning and Darcy–Weisbach equations have been used to infer fluid velocity and discharge rates in terrestrial gully and debris flow systems (Pierson, 1986; Mizuyama et al., 1988; Rickenmann and Zimmermann, 1993; Hessel et al., 2003; Govers et al., 2007; Garcia-Castellanos et al., 2009; Garcia-Castellanos and Villasenor, 2011; Levy, 2014). Examples include the use of Manning's equation to estimate velocity within steep-sided debris flows in Switzerland, which generally concurred with physically observed velocity values (Rickenmann and Zimmermann, 1993), inferring flow velocity in their development of a controlled steep gully environment and characterising the properties of vegetation in affecting water and sediment delivery (Molina et al., 2009). Manning's equation has also been used to infer velocity and discharges from Wright valley gullies in Antarctica by Levy (2014).

Gully dimensions – such as slope, channel width, depth and overall length – have been used in previous research to infer fluvial processes on Mars (Meyer et al., 1975; Gilley et al., 1990; Abrahams et al., 1996; Giménez and Govers, 2001; Di Stefano et al., 2013). De Santisteban et al. (2005) showed that gully eroded volume estimates were dependent on topographic conditions, such as drainage area, length, and slope. Although Govers (1992) postulated an independence of velocity and discharge from slope and regolith materials via feedback mechanisms, later work by Giménez and Govers (2001) showed that slope was definitely a factor in discharge and velocity estimates. This finding was in agreement with other investigations into power law relationships between discharge, mean velocity, width, depth, and slope (Meyer et al., 1975; Gilley et al., 1990; Abrahams et al., 1996). More recent field investigations conducted to characterise the erosion of rills and ephemeral gullies in Italy by Di Stefano et al. (2013) also highlighted the dependence of flow velocity to gully length, channel width, depth, and slope. Thus, in the absence of being able to directly observe and measure fluid flow in Martian gullies, inferences of velocity and discharge based on gully channel dimensions and slope remain a viable alternative.

Given the uncertainty as to whether Martian gullies result from debris flows or more fluidised flows, we constrained our gully velocity and discharge modelling to estimations derived from the Manning and Darcy–Weisbach equations. We used the Manning equation with a 20% variation of a roughness coefficient of 0.06. This was conducted in order to investigate the changes in inferred velocity and discharge calculations by providing upper and lower limits of velocity estimations through gully channels and account for uncertainties in deriving n for Martian gully channels. Our 20% variation straddles the 0.0545 Manning coefficient considered optimum for Martian channels (Wilson et al., 2004) and equates to terrestrial roughness ranging from streams with sand and gravel beds to shallower streams with rough beds consisting of multiple exposures of large cobbles and stones (Selby, 1991). We compared these results with estimations based on the Darcy–Weisbach Eq. (4) using Eq. (5) to calculate f. We calculated f based on D_{50} values of 0.144, 0.18, and 0.236 m, respectively, for the Reiss and Kaiser Crater sites described in Hobbs et al. (2013, 2014). These values are within the range of those suggested by Wilson et al. (2004) and Kleinhans (2005) and equate to particle sizes that would be on the threshold for detection by HiRISE imagery. Our previous research highlighted the utility of using thermal inertia to infer sediment particle sizes at our

Martian study sites given the difficulty in fixing this criterion in the absence of fieldwork (Hobbs et al., 2013, 2014). We note that the resolution of thermal inertia data sets [100 m/pixel, Thermal Emission Imaging System (THEMIS), 3 km/pixel Thermal Emission Spectrometer (TES)] is insufficient to resolve particle sizes within channels of specific gullies, particularly in the case of Kaiser Crater where only TES data were available. Exploitation of thermal inertia for hydrological analysis of our study sites would have led to mixing of pixel values at subinstrument resolution and probable underestimation of channel roughness. We thus were restricted to using particle sizes suggested by Wilson et al. (2004) and Kleinhans (2005) and performing a sensitivity analysis as described above.

Once flow velocity is resolved, it is possible to estimate the time duration of the flow between each cross-sectional profile and ultimately from the source:

$$t = D/v \qquad (8)$$

where D equals the length of each channel segment. The times between each cross-sectional profile can then be summed to provide a total duration of the flow. Uncertainties in estimations of time duration arise from the difficulty in calculating water flow through the gully alcoves. The Martian gully alcoves studied in this work possess a significantly different morphology to the underlying channels and are mostly larger, signifying a possible concentration of fluid in these regions. The calculations assumed a constant velocity from the gully head to the first channel cross-sectional profile. Velocity values can also be used to calculate flow discharge rates. Jouannic et al. (2012) and Parsons et al. (2013) used the product of channel width and height (approximate channel area) times velocity to derive discharge. The exploitation of HiRISE DEMS enables more accurate measurements of channel area, and the present work used the discharge rate, Q, equation exploited by Jouannic et al. (2012):

$$Q = Av. \qquad (9)$$

Estimations of discharge gave an indication of the erosive power of water in the gullies, as well as the amount of material eroded from the gully channel. In addition, we measured gully catchment sizes for the Martian and terrestrial gullies using the ArcGIS Spatial Analyst surface area tool. The size of the gully catchment provided an estimate of the contributing area to gully erosion (Lanza et al., 2010).

2.1. Slope

Previous workers have studied gully slopes (Heldmann and Mellon, 2004; Dickson et al., 2007; Kolb et al., 2010; Lanza et al., 2010; Conway et al., 2011) and often have used critical angles, such as the angle of repose (26–32°; Pouliquen, 1999) and dry mass wasting (>35°; Conway et al., 2011) to infer wet or dry erosive processes. Our previous research in comparing critical slope angles with distinctive morphology on the gullies at Kaiser Crater indicated the presence of dry mass wasting in the gully alcoves and steeper slopes (Hobbs et al., 2014). This suggests that gully shape may be altered by the interaction of a number of processes, consequently influencing hydrologic parameters such as channel roughness and wetted perimeter.

We performed classified slope analysis on Reiss Crater gullies using the same cutoff criteria as in Hobbs et al. (2014) (<21°, possible fluidised flow; 21–26°, transition between angle of kinetic friction and angle of repose; 26–35°, angle of repose; >35°, dry mass wasting). This was conducted in order to infer the presence and level of influence of potential dry mass wasting processes operating on the gullies, and hence their effects on hydrologic parameters. We also conducted a similar slope analysis on the southern ravines in Hobbs et al. (2013) to qualitatively compare nonfluvial activity with the gullies on the northern rim.

3. Material and methods

ArcGIS 3D analyst was used to exploit high resolution digital elevation models (DEMs) of Reiss Crater and Kaiser Crater sites. The Reiss Crater DEM was derived from a HiRISE stereo pair (ESP_011817_1395 and ESP_011672_1395) created using NASA Ames Stereo Pipeline (Moratto and Edwards, 2008; Broxton et al., 2011). As explained in Hobbs et al. (2013), we used a method similar to Broxton et al. (2011) to create our HiRISE DEM and checked for accuracy by comparing spot heights between the HiRISE DEM and a HRSC DEM. Although height measurements from the DEMs were comparable within the limits of the resolution provided by the HRSC DEM, shadowed regions of the HiRISE DEM produced frequency noise and spurious artefacts. These were mitigated by applying a 3 × 3 low pass filter to reduce frequency noise (Kolb et al., 2010) and by avoiding artefact-prone regions of the DEM. We chose gully channels for which DEM artefacts were at a minimum and extracted cross-sectional profiles to obtain wetted perimeter and hydraulic radius information. As an example, Fig. 5A shows the location of the cross-sectional profiles sampled at gully 2 at Reiss Crater. These cross-sectional profiles were used to generate cross sections covering morphological changes throughout the channel (Fig. 5B). The morphologies of the main channel and inset channel, where present, were captured in this manner, as highlighted by black and grey arrows in Fig. 5B, respectively. Of all the sampled Martian and terrestrial gullies, only Reiss Crater contained inset channels. We used lettering to annotate our studied terrestrial gullies (Figs. 2 and 3) and numbering to label gullies at our studied Martian sites (Fig. 4). All cross profiles were numbered sequentially from upper slopes to lower

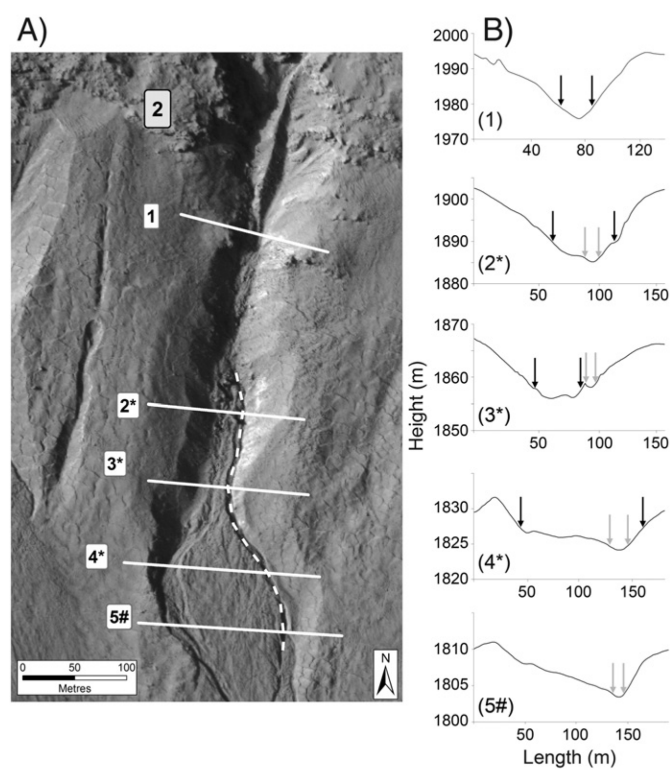

Fig. 5. (A) Methodology used to obtain channel parameters for studied Martian and terrestrial gullies. (A) Overview of gully 2 at Reiss Crater, showing locations of sampled channel cross-sectional profiles. Asterisks denote cross-sectional profiles where main channel and inset channel (marked by white dashed line) parameters were sampled, hash (#) denotes where just the inset channel was sampled. (B) Detail of gully channel cross-sectional profiles. Black arrows denote extents of primary channel, and grey arrows mark extents of inset channel where present.

slopes (Figs. 2–5). We exploited the Kaiser Crater DEM used by Kolb et al. (2010) that was created from a HiRISE stereo pair (PSP_003418_1335 and PSP_003708_1335) employing SOCET SET in the method described by Kirk et al. (2008).

We were not able to directly determine the physical height at which liquid water had flowed within our studied Martian gullies, given the lack of direct observations of liquid water. Although liquid water has been inferred as a possible agent within Recurring Slope Linea, active features that form during warm seasons and fade during cold seasons (McEwan et al., 2011), we could find no evidence of such features within our study area. We thus assumed our studied gullies behaved in a manner similar to incised streams on Earth (Schumm et al., 1984) where bankfull flow would be rare. Previous research has suggested Martian gully channels may enlarge via a series of smaller erosive events as opposed to a major failure (Hecht, 2002; Dickson and Head, 2009; Schon et al., 2009). We used imagery and topographical analysis to identify the thalweg of the gully channel and identified changes in channel slope along the cross-sectional profiles that may have indicated the possible height at which fluid within the gully channel flowed. We also undertook the process of analysing changes in slope as indicated by cross profile and image analysis for the larger and inset gully channels at Reiss Crater.

In order to obtain meaningful estimations of the main and inset channels, the inset channels were analysed separately by extracting their elevation from the combined channel cross-sectional profile. For analysis of the main channels, we removed the influence of inset channels by filling them with a constant elevation value along the main channel floor.

In the case of the terrestrial gullies, we were able to physically observe evidence of the height at which water had flowed within the gully channels, which typically had a maximum height of 50 cm above the channel floor. We chose the following calculation for f:

$$f = 8/\left(5.75\left\{1-\exp\left[(-0.05\mathrm{d_s})/\left(D_{90}S^{1/2}\right)\right]\right\} \times \log_{10}[8.2\mathrm{d_s}/D_{90}]\right)^2 \tag{10}$$

for the Darcy–Weisbach Lake George and Island Lagoon gully velocity and discharge estimates as this formula suited flows with steep slopes and multiple drop pools (Wilson et al., 2009). In contrast to the Martian sites, our previous research (Hobbs et al., 2013, 2014) revealed that the Lake George and Island Lagoon gullies possessed multiple breaks in slope, exposures of bedrock and plunge pools, which made the above calculation for f the ideal choice. Table 2 lists D_{90} values for each of the cross-sectional profiles for the Lake George and Island Lagoon gullies and is based on measurements of sediment sizes at different distances along the gully channel as gathered during our field surveys. As with the Manning equation, we performed sensitivity analysis of the velocity and discharge estimations by varying D_{90} by $\pm 20\%$. As the Martian gullies at both the Reiss Crater and Kaiser Crater sites presented a smoother profile with no observable plunge pools or bedrock exposures, we used Eq. (5) to calculate the friction factor for these features.

For the gullied channels 1, 2, and 3 at Kaiser Crater, there was no evidence of multiple flows, with no subsequent erosion or inset channels observed. Only flows within the gully channels were calculated, and the source of the flows for all gullies was assumed to be at the head of the alcove.

In summary our methodology assumed the following:

(A) Mass transport in gullies is predominantly fluid-mediated. Our terrestrial gully analysis summarised in Section 1.2 showed that the gullies we used for hydrologic analysis were primarily eroded by liquid water, with water directly observed flowing in some of them. Although evidence of additional processes was also observed, the morphology of our studied Martian gullies (Section 1.3) was consistent with liquid water erosion probably sourced from degradation of LDM or ice-rich crater wall material. Martian gully erosion by liquid water is also the mechanism favoured by most recent researchers (e.g., Heldmann et al., 2007; Dickson and Head, 2009; Mangold et al., 2010; Hernandez et al., 2014).

(B) Measured gully geometries, such as slope and cross-sectional geometry, provide sufficient information to estimate discharge. The use of gully dimensions, such as slope, channel width, depth, and overall length has been used in previous research to infer fluvial processes (Meyer et al., 1975; Gilley et al., 1990; Abrahams et al., 1996; Giménez and Govers, 2001; Di Stefano et al., 2013). Measured topographic parameters have also previously been used to infer velocity and discharge in Martian channels and gullies (Wilson et al., 2004; Kleinhans, 2005; Jaumann et al., 2008; Hart et al., 2010; Jouannic et al., 2012; Narlesky and Gulick, 2014).

(C) The grain sizes we chose for our analysis are appropriate. As described above we were able to directly measure the grain sizes that comprised the channels of our terrestrial gullies. We also performed a sensitivity analysis and allowed for grain size uncertainty by varying their values by 20%. In the case of the Martian gullies where no reliable data on channel bed roughness was available, we chose roughness range variances that straddled values used in previous research (Wilson et al., 2004; Kleinhans, 2005) and equated to particle sizes that would be on the threshold for detection by HiRISE imagery.

(D) The Manning and Darcy–Weisbach equations are applicable. These equations have been popular in velocity and discharge calculations in fluvial channels on Earth, Mars, and Titan (Selby, 1982; Sidorchuk et al., 2003; Wilson et al., 2004; Kleinhans, 2005; Jaumann et al., 2008; Parsons et al., 2013) and are being increasingly used to investigate Martian gullies (Hart et al., 2010; Jouannic et al., 2012; Narlesky and Gulick, 2014). We aimed to build on previous research by investigating the applicability of these equations to inferring the hydrology of Martian gullies and to compare these results with hydrological analyses of terrestrial gullies examined in previous work (Hobbs et al., 2013, 2014).

4. Results

Although DEM artefacts precluded classified slope analysis of gullies 1 and 2, the northeastern crater rim in which gully 3 resided (Fig. 6A) revealed a similar slope distribution to the Kaiser Crater gullies seen in Hobbs et al. (2014). The depositional fans resided below the angle of kinetic friction (Kolb et al., 2010). Slopes for the gully channel floors ranged from being below the angle of kinetic friction (<21°) to the transition between angle of kinetic friction to the angle of repose (21–26°). The slopes of the gully channels and depositional regions fell within the ranges that previous researchers have identified as indications of

Table 2
Grain size estimates for the studied gullies.

Gully	$D_{90}(2)$, m	$D_{90}(3)$, m	$D_{90}(4)$, m	$D_{90}(5)$, m	$D_{90}(6)$, m	$D_{90}(7)$, m
Martian gullies	N/A	N/A	0.24, 0.3, 0.375	0.24, 0.3, 0.375	0.096, 0.12, 0.15	0.096, 0.12, 0.15
LG_D	0.24, 0.3, 0.375	0.24, 0.3, 0.375	0.24, 0.3, 0.375	0.096, 0.12, 0.15	N/A	N/A
IL_E	0.32, 0.4, 0.5	0.24, 0.3, 0.375	0.16, 0.2, 0.37	0.08, 0.1, 0.125	N/A	N/A
IL_G	0.24, 0.3, 0.375	0.24, 0.3, 0.375	0.08, 0.1, 0.125	N/A	N/A	N/A

LG: Lake George; IL: Island Lagoon.

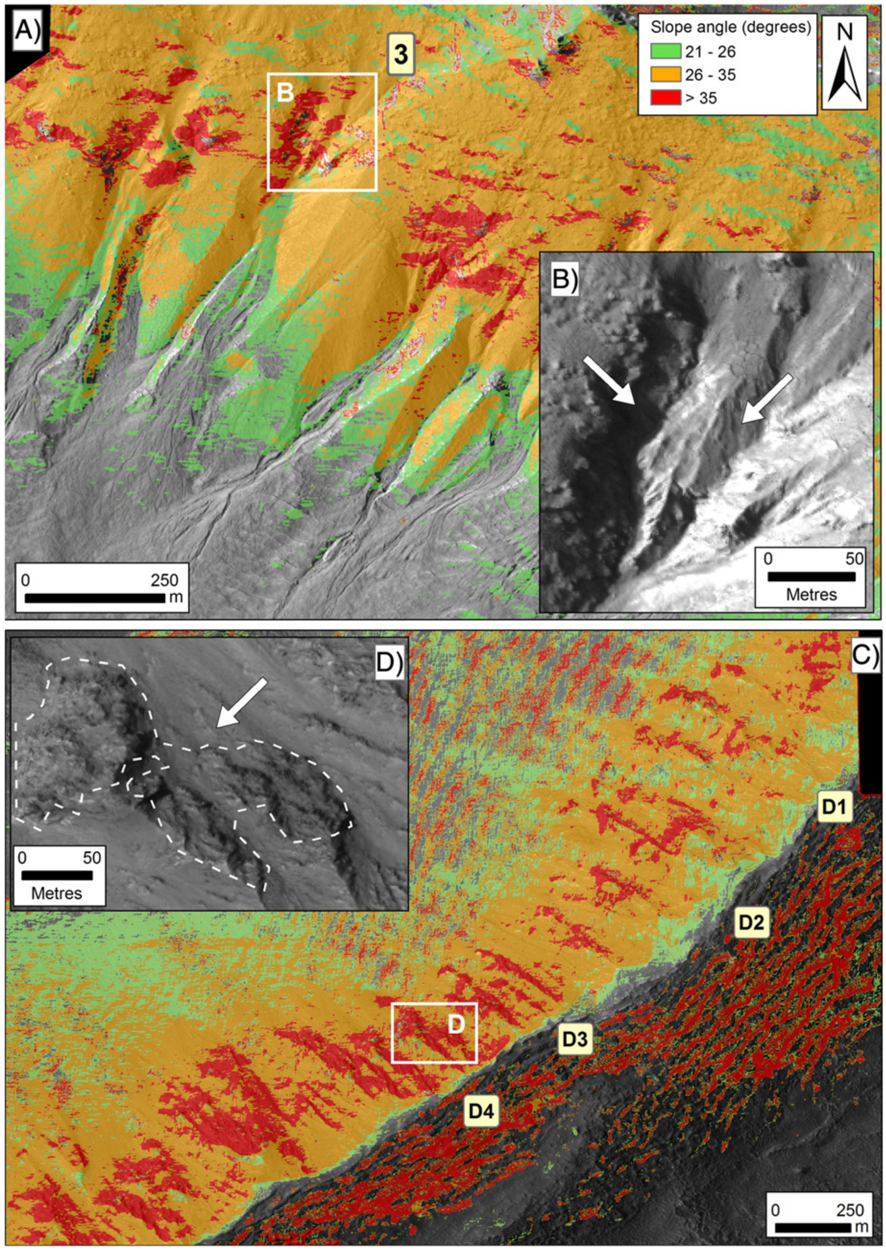

Fig. 6. Slope analysis of northern gullies and southern ravines of Reiss Crater as derived from exploitation of the HiRISE DEM. (A) Classified slopes of northern gullies revealing sporadic high (>35°) values in upper channels and alcoves and low (<21°) slopes in the depositional regions. Extent of B is shown and black areas mark exclusions caused by DEM artefacts. (B) Detail of high slope region revealing spur and gully morphology as highlighted by white arrows. (C) Classified slopes of southern ravines revealing greater abundance of high (>35°) values than northern gullies. Extent of D is shown. (D) Detail of high slope area revealing rocky outcrop (highlighted by arrow and dashed line) bounding ravine alcove.

erosion by liquid water (Heldmann and Mellon, 2004; Kolb et al., 2010; Mangold et al., 2010; Conway et al., 2014). Thus, liquid water has likely been primarily responsible for the majority of erosion at Reiss Crater. As might be expected, the walls of the incised channels possessed steep slopes within the same 26–35° range as most of the crater wall. Sporadic regions within the uppermost channels and alcoves, where present, possessed slopes > 35°, though angles within the alcoves, where present, typically resided in the 30–35° range. This indicates the possible presence of dry talus flows in these areas, and detailed analysis (Fig. 6B) revealed that spur and gully morphology occurred exclusively in these regions.

Classified slope analysis of the southern ravines revealed a greater abundance of high slope values, and all but the lowest extent of the depositional fans present possessed angles greater than the angle of kinetic friction (Fig. 6C). As highlighted by the dashed line and arrow in Fig. 6D, the >35° slope areas in the ravines predominantly occurred where prominent rocky outcrops bounded the ravine alcoves.

Velocity and discharge analysis using a range of roughness coefficients resulted in a variation of final value of up to 25%. This reveals that hydraulic flow estimations are sensitive to initial estimations of roughness coefficients and highlights the difficulty in selecting appropriate values for Martian channels. Table 3 shows catchment area, velocity, and discharge rate using the Manning and Darcy–Weisbach equations. For Reiss Crater gullies, Darcy–Weisbach estimates of velocity and discharge rates were consistently higher by ~30%, and time values were lower than those derived from the Manning equation, except for gully 2's main channel. Fig. 7 plots mean velocity and discharge estimates from Manning and Darcy–Weisbach equations along with one standard deviation from the mean. Manning flow velocities for gully 1 at Reiss Crater, using n values of 0.048–0.072 and D_{50} values of 0.144–0.236 m ranged from 2 to 5 m s^{-1} with flow duration ranging from 138 to 207 s for the flow to travel from the source to the end of the last sampled profile, while Darcy–Weisbach velocity was 3 to

Table 3
Summary of hydrology parameters for studied Martian and terrestrial gullies. These have been classified by inferred hypothesis mechanism that is explained in the discussion.

Gullies for which surface runoff multiple event erosion is inferred:			
Reiss Crater	Coordinates: 40°: 21′S 20°: 06′E	Location: Northern crater wall	HiRISE: ESP_011817_1395
Gully	Catchment area (m^2)	Velocity V; M/DW ($m\ s^{-1}$)	Discharge Q M/DW ($m^3\ s^{-1}$)
R_1	91,580	2–5/3–7	17–54/21–65
R_2 inset	Unknown	2–5/2–6	5–18/5–21
R_3 inset	Unknown	2–6/2–7	6.5–25/8–28
Kaiser Crater	Coordinates: 46°: 05′S 18°: 45′E	Location: Northern crater wall	HiRISE: PSP_003418_1335
Gully	Catchment area (m^2)	Velocity V; M/DW ($m\ s^{-1}$)	Discharge Q M/DW ($m^3\ s^{-1}$)
K_1	134,000	2–4/2–4	5–15/7–16
K_2	152,645	2–3/2–4	6–13/7–14
K_3	79,885	1–4/1–6	4–42/4–57
Gullies for which multiple event top down erosion with subsequent widening by dry mass wasting is inferred:			
Reiss Crater	Coordinates: 40°: 21′S 20°: 06′E	Location: Northern crater wall	HiRISE: ESP_011817_1395
Gully	Catchment area (m^2)	Velocity V; M/DW ($m\ s^{-1}$)	Discharge Q M/DW ($m^3\ s^{-1}$)
R_2 main	156,350	5–9/8–12	141–911/209–1206
R_3 main	190,100	6–12/11–17	321–801/577–1090
Gullies for which surface runoff multiple event erosion is inferred:			
Lake George	Coordinates: 35°: 06′S 125°: 22′E	Location: Western escarpment	
Gully	Catchment area (m^2)	Velocity V; M/DW ($m\ s^{-1}$)	Discharge Q M/DW ($m^3\ s^{-1}$)
LG_A	31,070	1–3/1–3	3–7/2–5
LG_D	21,290	1–3/1–2	1–7/1–4
Island Lagoon	Coordinates: 31°: 23′S 136°: 55′E	Location: Northern escarpment	
Gully	Catchment area (m^2)	Velocity V; M/DW ($m\ s^{-1}$)	Discharge Q M/DW ($m^3\ s^{-1}$)
IL_E	112,500	1–2/1–2	1–4/1–3
IL_G	153,030	1–2/0.5–1	1–4/1–3

R: Reiss Crater; K: Kaiser Crater, LG: Lake George; IL: Island Lagoon; M Manning; DW Darcy–Weisbach.

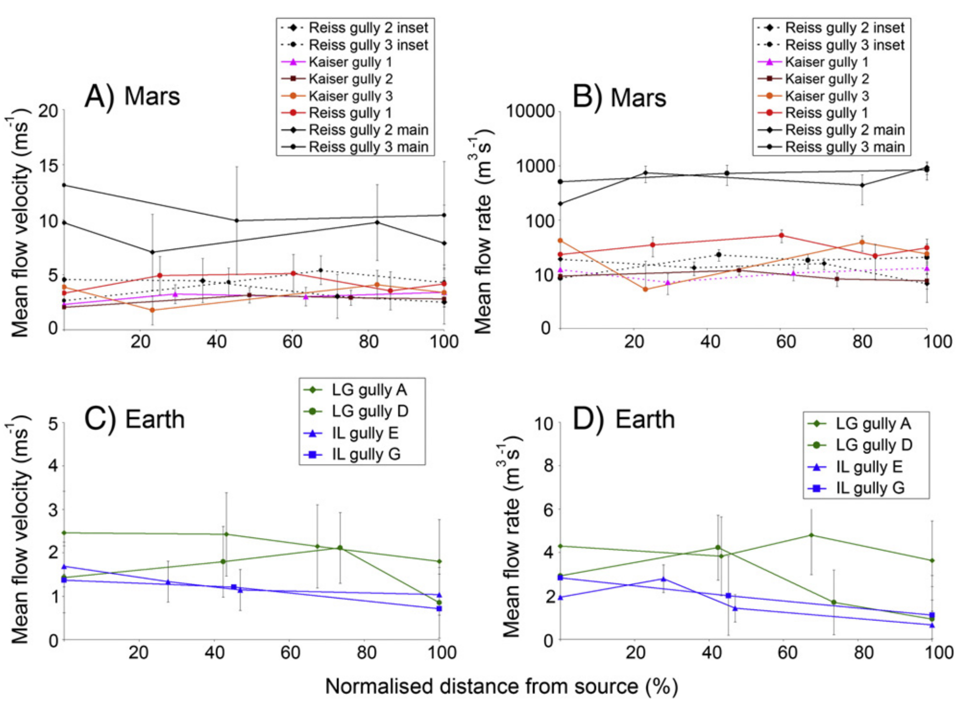

Fig. 7. Plots of mean Manning and Darcy–Weisbach velocity and discharge rates as a function of normalised distance from the source for the studied Martian and terrestrial gullies. Error bars mark one standard deviation from the mean. Distances have been normalised by total distance for each gully channel and first measured cross profile has been placed on the origin. Colour coding for this figure reflects that of Figs. 2–4. (A) Mean velocity for studied Martian gullies. (B) Mean discharge rate for studied Martian gullies. (A) Mean velocity for studied terrestrial gullies. (B) Mean discharge rate for studied terrestrial gullies.

7 m s^{-1} (Table 3) with flow duration ranging from 90 to 130 s. These velocity values approximated the typical ranges of terrestrial debris flows (0.5–10 m s^{-1}; Rickenmann, 1999) and correlated with previous findings of Martian gully velocities (Mangold et al., 2003; Jouannic et al., 2012), though they did not show a decrease in value from the top to the bottom of the gully. This contrasts with the findings of Jouannic et al. (2012), where a decrease in velocity was observed from the head to the depositional area of their analysed Russell Crater dune gully.

Velocity estimates for Reiss Crater gully 2 inset channel using the two hydrology equations ranged from 2 to 6 m s^{-1} (Table 3, Fig. 7A), and flow duration ranged between 187 and 281 s. The inset channel of gully 3 also shows comparable values, with velocity ranging from 2 to 7 m s^{-1} and times ranging from 204 to 156 s. Gully 3 inset channel velocities increased from source to depositional area in a similar manner to gully 1. As shown in Fig. 7B, discharge rates using the Manning and Darcy–Weisbach equations for gully 1 ranged between 17 and 65 m^3 s^{-1} (Table 3). These figures were also within the range of the discharge rates of the inset channels in gullies 2 and 3 (Fig. 7B), which ranged between 5 and 21 m^3 s^{-1} and between 6.5 and 28 m^3 s^{-1}, respectively (Table 3). As with the inferred velocities, these discharge rates generally concurred with terrestrial discharge rates.

Analysis of the main channels of the larger Reiss Crater site gullies 2 and 3 revealed significantly higher flow velocities and discharge rates. As shown in the main channel values in Fig. 7A, the velocities of gully 2 ranged between 5 and 12 m s^{-1} (Table 3), decreasing downslope while discharge rates ranged between 141 and 1206 m^3 s^{-1} (main channel values, Fig. 7B). The velocities for gully 3 were also high (main channel values, Fig. 7A), with velocities ranging between 6 and 17 m s^{-1} (Table 3), sharply decreasing downslope while discharge rates ranged between 321 and 1090 m^3 s^{-1} (main channel values, Fig. 7B).

Values of flow velocities and discharge rates for the Kaiser Crater gullies using the Manning and Darcy–Weisbach equations and other key parameters for these gullies are comparable to those of the inset channels of Reiss Crater (Fig. 7A–B, Table 3), and within the low end of figures for terrestrial debris flows (Rickenmann, 1999). Gully 1 possessed velocities ranging between 2 and 4 m s^{-1}, and discharge rates ranging between 5 and 16 m^3 s^{-1} (Table 3). The velocity (2–4 m s^{-1}) and discharge rate (6–14 m^3 s^{-1}) ranges for gully 2 were less than the velocity (1–6 m s^{-1}) and discharge rates (4–57 m^3 s^{-1}) of gully 3 and were the lowest of all analysed Martian gullies. The relatively low velocity values of Kaiser Crater gullies 2 and 3 reflect the smaller sizes of their channels as compared to the larger Reiss Crater gullies. The velocity estimates for the Kaiser Crater gullies remained relatively constant downslope (Fig. 7A), though trends in the discharge rates were less distinct than velocity trends (Fig. 7B). These may indicate variations of size within the channel as with the gullies at Reiss Crater, coupled with relatively linear slopes observed in their profiles (Hobbs et al., 2014). The times taken for the gully discharges to travel from head to depositional areas were approximately twice those of Reiss Crater ranging from 231 to 343 s. This is an indication of the increased distance from the flow source within the alcoves for these gullies, as well as the lower velocities at which the fluid had travelled.

Fig. 7C and D and Table 3 summarise the velocity and discharge estimates for Lake George gullies A and D. With the exception of Lake George gully A Manning discharge and gully D Darcy–Weisbach discharge, these gullies show a decreasing trend in values as a function of distance, more so than the Martian sites (i.e., compared with Fig. 7A–B for the Reiss and Kaiser Crater sites). Velocity estimates for Lake George gully A ranged between 1 and 3 m s^{-1}, with discharge rates ranging between 2 and 7 m^3 s^{-1}. Gully D velocity also ranged between 1 and 3 m s^{-1}, with a discharge rate range of 1 to 7 m^3 s^{-1}. Times for these flows ranged from 88 to 200 s for gully A and 142 to 287 s for gully D.

Despite being located in a semiarid environment, the Island Lagoon gullies' velocity and discharge estimates were similar to those of Lake George (Fig. 7C–D, Table 3). Island Lagoon gully E had velocity ranges of 1 to 2 m s^{-1} with discharge rate ranges of 1 to 4 m^3 s^{-1}. Island Lagoon gully G velocities ranged between 0.5 and 2 m s^{-1}, with discharge rates ranging from 1 to 4 m^3 s^{-1}. Time durations for flows at these gullies ranged from 87 to 221 s.

5. Discussion

Analysis of hydrologic characteristics of Reiss Crater highlighted the complex nature of gully erosion in this region. The irregular velocity and discharge values from gully 1 (Fig. 7A–B) indicate a complex morphology for its channel, which widens midway downslope (Fig. 4A), leading to an increased cross-sectional area and presumably decreased velocity at that point. These irregularities are also observed in other gullies, with the main channels of gullies 2 and 3 at Reiss Crater, presenting a decrease in flow velocities and discharges downslope. The mean velocities for gully 1 and the inset channels of gullies 2 and 3 appear very similar (Fig. 7A). They also correlate with the velocities we inferred for the Island Lagoon and Lake George gullies (Fig. 7C). Correlation was less between the mean discharge rates of these gullies, with the estimated discharges of Reiss gully 1 being higher than for the Kaiser and inset gullies (Fig. 7B). We note that the larger channel of Reiss gully 1 as compared to the Reiss inset channels and Kaiser gullies may have been an influencing factor in the higher discharge estimate for this gully. The discharges for these gullies were also higher than those for Island Lagoon and Lake George (Fig. 7D) though all estimated velocities and discharges for these Martian gullies fall within the range for terrestrial flows (Rickenmann, 1999) and for results of the dune gully studied by Jouannic et al. (2012).

The velocities and discharge rates for the main channels at Reiss Crater are an order of magnitude larger than for the inset channels and were consistent with large-scale debris flows with high volumes of debris measured on Earth, such as the Swiss Alps or Columbia (Rickenmann, 1999). Previous studies by Parsons and Nimmo (2010) and Narlesky and Gulick (2014) have also inferred high velocities and discharge volumes for their gully flow estimations that correlate with our findings for the larger channels of Reiss Crater gullies 2 and 3. Additionally, previous research has indicated debris flows typically contain 30 to 40% water by volume (Iverson, 1997; Rickenmann, 1999). This suggests that the large channels of gully 2 and gully 3 were eroded by discharges with an upper limit of the water component being up to 335 m^3 s^{-1}. If we assume an upper limit of flow time of ~114 s (gully 2, Reiss Crater) for the larger gullies and a continuous source of flow for this time, a total volume of 38,190 m^3 of water is reached. This upper estimate of water volume for the largest gully channels we studied is much less than the 1.8×10^6 m^3 of total water inferred by Parsons and Nimmo (2010) for gully erosion, though far greater than the flow volume of 1500 m^3 inferred by Heldmann et al. (2005). We will now consider these results in the context of three hypotheses for Martian gully formation: aquifer discharge; single, top down melting event; and multiple, smaller melting events.

5.1. Aquifer hypothesis

We considered the possibility of aquifer-fed water as a potential erosive source, as originally suggested by Malin and Edgett (2000). This hypothesis would allow for groundwater outbursts from shallow aquifers, feeding gully erosion. Geomorphological indicators for such a process would be the correlation between gully source regions and competent bedrock layers that would provide a conduit for aquifer discharge, such as channels emanating from bedrock layers (Malin and Edgett, 2000; Gilmore and Phillips, 2002; Dickson and Head, 2009). We were unable to find evidence of any such association between bedrock layering and all of our studied gullies appeared to be embedded within incompetent regolith, and at elevations not consistent with an aquifer-fed seepage layer. The gullies at Reiss Crater appeared to be embedded within ice-rich mantling material similar to that observed in previous research (Christensen, 2003; Schon and Head, 2011, 2012; Araki, 2012) with drainage of degradation of this material appearing to feed the gully heads (Fig. 4A–C). Similarly we observed no bedrock layering in any of the Kaiser Crater gullies, and alcoves had clearly eroded in a manner not suggestive of structural control. Examples of this inconsistency include Kaiser gully 1 eroding much farther upslope (Fig. 4D), while the topmost extent of Kaiser gullies 2 and 3 alcoves was located at random elevations farther downslope (Fig. 4E–F). If these gullies were fed by an aquifer, we would have expected greater consistency between elevations of the gully alcoves and the presence of a competent bedrock layer. We thus believe that the aquifer hypothesis is not appropriate for explaining the morphology of the gullies at our study sites.

5.2. Top down melting — single event hypothesis

Top down melting of snow or ice-rich material is currently the favoured hypothesis for the formation of Martian gullies (Costard et al., 2002; Hecht, 2002; Dickson and Head, 2009; Schon and Head, 2011, 2012; Levy, 2014). Seasonal water frost accumulation has been observed at sheltered pole-facing slopes of present-day Mars (Schorghofer and Edgett, 2006; Vincendon et al., 2010), and thermal modelling has suggested that pole-facing slopes are favoured locations for melting of snow and near surface ice (Costard et al., 2002; Dickson and Head, 2009). The polygonal texturing at Reiss Crater (Hobbs et al., 2013) and previous research performed on the Kaiser Crater gullies (Conway et al., 2011) indicates that the gullies at our study site are embedded within ice-rich material (Levy et al., 2009; Schon and Head, 2012).

The morphology of the studied Kaiser crater gullies, gully 1, and the inset channels of gullies 2 and 3 of Reiss Crater shows a lack of evidence of multiple, subsequent flows and instead suggests that channel formation may have occurred as single events. We note that the velocity and discharge values of the gully 2 and 3 inset channels of Reiss Crater correlated with those of the Kaiser Crater gullies, and our calculations of Lake George and Island Lagoon gully velocities and discharges. This suggests that the smaller channels we studied may have been formed by processes of a similar scale. A summary of hydrological parameters for the Martian gullies correlating with the top down, single discharge hypothesis is given in Table 3. Assuming water concentrations of 40%, the maximum amount of water required for discharge for the smaller gullies would be of the order of 25 $m^3\ s^{-1}$. This estimate correlates with medium-scale, single-event terrestrial failures (Rickenmann, 1999) as well as previously published results for Martian gullies (Hart et al., 2010; Jouannic et al., 2012). A single discharge event is thus a plausible scenario for the erosion of inset channels of Reiss Crater and the Kaiser Crater gullies. We suggest that additional processes, such as dry mass wasting and frost creep, have also acted on the Kaiser Crater alcoves, particularly the high slope areas (Hobbs et al., 2014). In addition, based on the lobate aprons and leveed lower channels at the Kaiser Crater site, the lower portions of these gullies may have experienced debris flow activity. This differs from the possible mix of fluvial/debris flow mechanisms of Reiss Crater, though unambiguous evidence for fluvial or debris flow activity is lacking for all of our studied Martian gullies. Thus, fluvial flow is probably the dominant erosive mechanism acting on these gullies.

5.3. Top down melting — multiple events hypothesis

The large velocity and discharge estimates for the main channels of gullies 2 and 3 correlate with similar findings for larger Martian gullies (velocity of ~20 $m\ s^{-1}$, Narlesky and Gulick, 2014; Levy, 2014; discharges of ~1000 $m^3\ s^{-1}$; Levy, 2014) and equate to terrestrial rivers capable of large-scale erosion (Whipple and Tucker, 1999). No evidence of large-scale movement of rocks, erosion to bedrock, or floodplains was observed in the main channels of gullies 2 and 3, possibly arguing against this level of activity. In addition, it is hard to reconcile the upper limit of ~38,000 m^3 of water required for this scale of event with the difficulty in maintaining and releasing such quantities under Amazonian Martian conditions, which is a point also acknowledged by Narlesky and Gulick (2014). We estimated the total volume of sediment eroded from the alcoves of each gully, based on the contributing area calculations in Table 3 and a maximum erosion depth estimated to be 3 m, assuming that constant sediment/ice mixing would be at most 1 km^3 per alcove. The small contributing area sizes and thus potential availability of water for erosion infer that single event snowpack melting would not be likely in providing the amounts of water for this scale of gully erosion, requiring ice thicknesses of up to 1 km (Russell and Head, 2007).

Although single, large-scale catastrophic events cannot be entirely ruled out for the larger gully channels using our study methods, it is far more likely that the main channels of gullies 2 and 3 were eroded by a series of smaller flows over a period of time, possibly linked to obliquity cycles and progressive deposition and erosive events. The concept of accumulated erosion by smaller events to create larger features is a common hypothesis in terrestrial geomorphology (Selby, 1991), such as examples of larger gullies eroding from smaller rill flows (Selby, 2000). The hydrological results we inferred (multiple event, top down erosion hypothesis, Table 3) thus suggest that the main channels of gullies 2 and 3 were formed through different processes than the inset channels, gully 1, or the Kaiser Crater gullies (single event, top down erosion hypothesis, Table 3).

We observe that the lower half of the gully 2 channel (below cross profile (2)2, Fig. 4B) and the channel of gully 3 at Reiss Crater (Fig. 4C) appear to have been partially infilled with mantling material. Recent work by Dickson et al. (2013) and Levy et al. (2014) based on McMurdo Dry Valley evolution and the observations of LDM removal and replacement suggests that some Martian gullies have been subject to multiple reworking events. This raises the possibility that the ice-rich material infilling the channels of gullies 2 and 3 is younger than the main channels and that the inset channels may represent a smaller, second generation of gullies eroding from this material, creating inset channels and superposed depositional fans (Fig. 4C). This reworking has also probably erased or at least extensively modified the original gully channel, such as the infilling observed in the gully 3 main channel. This is also suggested by visible polygonal overprinting within the main channels of gullies 2 and 3 at Reiss Crater, which is absent in the infilled material and inset channels within the gullies.

The main channels of the larger gullies may have originated from smaller flows similar in size to the inset channels, and bankfull discharges did not occur regularly. Smaller flows, occurring repeatedly over time in similar locations, would serve to enlarge the channels in a similar manner to that observed in terrestrial systems (Selby, 1991, 2000; Thomas, 2011). Slope analysis of the walls of the larger gully channels at Reiss Crater revealed values and morphologies that were consistent with nonfluvial processes, such as dry mass wasting (Fig. 6A–B). We observed frost shattering and talus flows operating on the steeper gully channel walls in our study of the terrestrial gullies at Pasture Hill, New Zealand (Hobbs et al., 2014). Dry mass wasting of the steeper gully walls, as suggested by slope analysis of these features (Fig. 6A–B) may have increased the channel width, creating regions for infilling of ice-rich mantling material and a water source for subsequent fluvial erosion. In addition, post-fluvial modification by dry mass wasting may have also provided artificially inflated channel cross-sectional areas, thus driving up estimates for flow velocities and discharge rates. Although DEM artefacts precluded analysis of gullies 1 and 2, these high values were not present on the walls of the inset channel of gully 3 of Reiss Crater, or in any of the Kaiser Crater gully channels. Post-fluvial channel widening by dry mass wasting is therefore less likely to have occurred in these regions.

5.4. Surface runoff

We noted velocity and discharge estimates for Lake George gullies (velocity 1–3 $m\ s^{-1}$, discharge 1–7 $m^3\ s^{-1}$) correlated with those at

Island Lagoon (velocity 0.5–2 m s^{-1}, discharge 1–4 m^3 s^{-1}), despite these gullies being located in different environments (Table 3, Fig. 7C–D). These values fall within the range of smaller scale, previously researched terrestrial events (Rickenmann and Zimmermann, 1993; Rickenmann, 1999).

Neither the Lake George nor the Island Lagoon main gully channels displayed evidence that they hosted debris flows, though as discussed in Section 1.2 small debris flows were observed on the escarpment walls surrounding the Island Lagoon gully site. No leveed channels or lobate aprons on the main channels were observed, and both sites showed clear evidence of gully formation and evolution by surface runoff. In the case of the Island Lagoon gullies, catchment fed runoff channels above the gully alcoves were observed, facilitating gully erosion. Multiple erosive events may also have affected the gully channel morphology and subsequently influenced our hydrological results summarised in Table 3. Although subsequent erosion and revegetation may have removed evidence of debris flows at the Lake George site, it is more likely that gullies at both terrestrial sites were formed by fluvial flows with higher concentrations of water present than the Martian gullies. Although leveed channels were observed at the Kaiser site and the inset channel of gully 2, our assessment is that although debris flows may have possibly occurred at our studied Martian sites, they were not a dominant process. This contrasts with work conducted by Johnsson et al. (2014) where strong evidence of debris flow activity was observed within a gullied ray crater in the Aonia region.

At the Lake George and Island Lagoon gully sites, we observed that subsequent channels embedded within larger channels and incised depositional fans provided additional evidence for multiple fluvial events occurring on these gullies (Hobbs et al., 2013, 2014). Thus the physical height at which we observed water flowing in the terrestrial gully channels and on which we based our calculations may represent the latest fluvial discharge. Historic erosion of the magnitude we inferred in our calculations as occurring multiple times has probably incised the gully channels to the depth we see in the present day. In the case of Lake George, vegetation has overgrown segments of the gully channels, indicating that erosion in this area may consist of multiple, sporadic events. As with the Martian gullies, trends from high to low velocities and discharge rates as gully slope decreased were difficult to detect. Gully A at Lake George and gully E at Island Lagoon (Fig. 7C–D) were the only gullies to clearly display a smooth decrease in values, though overall decreasing trends were also present for Island Lagoon gully G (Fig. 7C–D).

5.5. Roughness parameters

Although gully velocity and discharge estimates of Martian and terrestrial gullies varied by as much as 40% when using the Manning equation compared to the Darcy–Weisbach equation, the results generally concurred with results for terrestrial debris flows (Rickenmann, 1999) and previous research for Martian gullies (Heldmann et al., 2005; Parsons and Nimmo, 2010; Jouannic et al., 2012; Levy, 2014). Previous research has suggested that the Darcy–Weisbach equation should be preferentially used over the Manning equation owing to its updated terrestrial friction factor benchmarks, nonreliance on empirical parameters and its explicit inclusion of gravity (Wilson et al., 2004; Kleinhans, 2005). We found the greatest uncertainty to reside in estimates for channel roughness and determination of suitable friction factors. Estimates of f based on terrestrial analogues are limited given the vast differences between the warm, wet climatic conditions of Earth and the hyperarid, rarefied environment of Mars. In addition, although a debris flow hypothesis is a possible mechanism for Mars gully formation, given that it requires less water to operate, there is no consensus as to whether it has operated on all Martian gullies (Reiss et al., 2011). Our research suggests that other processes may operate in conjunction with or independently of debris flows on Martian gullies, including nonfluvial erosion such as dry mass wasting indicated by probable dry wasting features identified in Fig. 6.

Detailed composition and hence roughness of Mars gully channels remain the province of future lander missions to Martian gully sites, and previous usage of the Darcy–Weisbach equation has relied on inferences of regolith sizes from previous Mars landing sites. These sites, by necessity for spacecraft safety, have been relatively flat regions that bear little resemblance to the steep, V-shaped channels that characterise Martian gullies. None of the Martian gullies we studied were eroded to bedrock, indicating that channel roughness would be less than that of the Island Lagoon and Lake George gullies. Thus, given the limitations of inferring friction factors for Martian regolith, we suggest that the Manning and the Darcy–Weisbach equations are suitable for inferring gully velocities and discharge rates and that hydrological inferences from channel morphology and slope, as used in previous studies (Meyer et al., 1975; Gilley et al., 1990; Abrahams et al., 1996; Di Stefano et al., 2013) are valid.

6. Conclusions

We studied two gully sites in Noachis Terra, Mars, and two terrestrial analogue sites in order to infer the power of proposed fluvial erosive mechanisms acting on them. We inferred flow velocities and discharge rates using the Manning and Darcy–Weisbach equations. We performed a sensitivity analysis to mitigate uncertainties in roughness coefficients and friction factors used in both formulae, originating from incomplete knowledge of Mars gully regolith. We found that the velocities for the terrestrial gullies ranged from 0.5 to 3 m s^{-1}, with discharge rates ranging from 1 to 7 m^3 s^{-1}. These results were comparable with previous research on terrestrial erosion and similar to velocities of the smaller Martian gully channels ranging from 1 to 7 m s^{-1} and discharge rates ranging from 4 to 65 m^3 s^{-1}. These values were within the range of postulated top down erosion mechanisms for Martian gullies. We thus infer that these channels were likely formed by single discharges of liquid water from accumulated ice-rich deposits. In contrast, velocity and discharge estimates of the larger gully channels were very high, ranging from 5 to 17 m s^{-1} and from 141 to 11206 m^3 s^{-1}, respectively. These results equated with highly catastrophic debris flows on Earth. Given the difficulty in having vast amounts of liquid water for such processes being stable under Martian conditions, we conclude that the larger gully channels were more likely formed by a different process involving a number of smaller discharges. These discharges were possibly at a scale approximating the smaller gullies we studied. An accumulation of these smaller events occurring over time may have widened the gully channels to their current size. In addition, slope analysis of these larger Martian gullies suggested channel widening through nonfluvial erosion such as dry mass wasting has also occurred, though the morphology of all studied gullies suggests liquid water has been the dominant erosive agent acting on them. We found that velocity and discharge rates varied considerably throughout all of the studied gullies in response to changing dimensions of the gully channel, affecting cross-sectional areas and hydraulic radii and, to a lesser extent, gully slope. Future hydrological studies on Martian gullies, along with lander missions to characterise gully channel regolith, will shed further light into the role liquid water plays in shaping the Martian surface.

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